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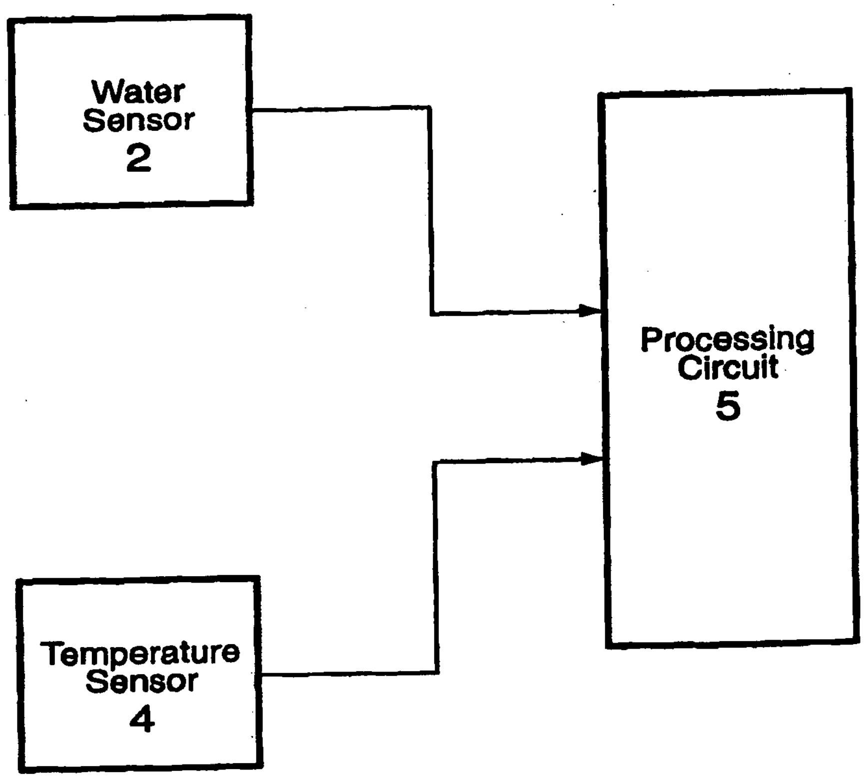
(57) Abstract

The present invention provides a water sensing system for sensing the water content of a liquid and communicating water content information to an operator. Communicating water content information may include processing the sensed water content value and comparing the value to one or more threshold values to qualify the sensed value. According to another aspect, the water sensor includes isolated 4–20 mA interface outputs for use with external devices such as programmable logic controllers. According to another aspect, the present invention provides a water sensing system which senses a relative water content value and converts the relative water content value to an absolute water content value. According to another aspect, the present invention includes methods and circuitry for calibrating a water sensing system. According to yet another aspect, the present invention provides a liquid purification system to sense the water content of a liquid and remove water from the liquid using a purifier.



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Methods and Systems for Sensing Water in Liquids

This application claims the benefit of U.S. provisional patent application 60/043,566, filed April 14, 1997; U.S. provisional patent application 60/060,058, filed September 25, 1997; and U.S. provisional patent application 60/074,315, filed February 11, 1998; the disclosures of all of which are hereby incorporated by reference.

TECHNICAL FIELD

The present invention relates to methods and systems for sensing water in liquids. More particularly, the present invention relates to methods and systems for sensing water in oils, hydraulic fluids, and other liquids in which it is desirable to monitor and/or control water content.

BACKGROUND OF THE INVENTION

Liquids, including oils, such as transformer oils, motor oils, transmission fluids, etc., may become contaminated with water and other materials during use. Liquids contaminated with water and other materials cause corrosion, wear, and mechanical damage to devices using contaminated liquids. Accordingly, it is desirable to sense and remove contaminants such as water from the liquids.

Conventional methods for determining the water content of liquids, such as Karl Fischer titration, involve sampling the liquid, sending the sample to a lab, and adding a reagent to the sample to measure the water content. This method is undesirable for a variety of reasons. First, it is time consuming. Second, the water content of a liquid may change from the time a sample is obtained to the time when the results of the test are returned from a lab. Thus, a water content test which cannot be performed on-site and within a reasonable time after sampling may be unreliable.

One way to characterize the water content of a liquid is relative water content, such as percent relative humidity (%RH). Percent relative humidity is a measure of the water content of a material relative to the saturation point of the material at a given temperature. For example, the percent relative humidity of an oil may be 50% at 100 degrees Fahrenheit. This indicates that the oil is 50% saturated at that temperature, or,

alternatively, a 50% RH reading indicates that the oil can absorb the same amount of water already in solution before the oil becomes saturated and water comes out of solution at that temperature.

In liquids in which the operating temperature varies over a wide range, it may be desirable to measure the absolute water content rather than the relative water content because relative water content varies with temperature. In other instances in which the operating temperature of a liquid remains relatively stable, %RH provides a useful measure of the water content of a liquid.

For a fixed absolute water content in a liquid, the %RH decreases with increasing temperature and increases with decreasing temperature. This temperature dependency of %RH measurements may lead to a false indication that the water content of a liquid is within acceptable limits. For example, a technician may measure the %RH of a transformer oil during operation when the oil is at an elevated temperature and find that the %RH is 50%. Since the oil is only 50% saturated, the technician may conclude that the water level is within acceptable limits. However, after the transformer shuts down, the temperature of the oil decreases, and the %RH rises. If the %RH rises to 100%, the water dissolved in the oil will come out of solution and condense to form droplets in the oil. The undissolved water may combine with other contaminants in the oil and cause corrosion of the transformer. Undissolved water in transformer oil can also reduce the dielectric strength of the oil and may cause arcing. Thus, a low %RH measurement for a liquid in which the temperature may decrease may not indicate a safe water content for the liquid. Accordingly, there exists a need in the industry for a water sensing system which compensates for the temperature dependency of %RH measurements.

Another problem that exists is the presence of undissolved water in liquids used in hydraulic, lubrication, and transmission systems. Undissolved water may cause wear and damage to mechanical components. For example, if undissolved water in a hydraulic liquid freezes, the water expands and may cause damage to components, such as valves. Undissolved water may also break down a lubricating liquid and cause wear of mechanical components. Undissolved water can also react with additives or the lubricating liquid itself to form acids which may corrode mechanical components. Furthermore, undissolved water itself can corrode mechanical components through

oxidation. Accordingly, there exists a need in the industry for accurately and conveniently determining the water content of a liquid.

As stated above, in some instances, it may be appropriate to measure absolute water content, and in other instances, it may be appropriate to measure relative water content, such as %RH. Features which are needed in a sensor which provides either measurement is the ability to function in an on-line, i.e., real time, environment where water content is measured in-line, the ability to provide quick and accurate measurements, and the ability to exist inside the liquid without significantly decreased performance. A partial solution to the problems associated with conventional water detection techniques is to remove the water from a liquid without sensing the water content. A purifier, e.g., a spinning disk purifier, a nozzle purifier, or a tower purifier, may be used to remove water from liquids. Typically, a liquid is circulated through the purifier to remove water and other contaminants from the liquid. Purification results may be verified through conventional water detection techniques, such as Karl Fischer titration. Because of the time and reliability problems associated with conventional water detection techniques, these techniques may be undesirable for on-line purification operations. Thus, there exists a need in the industry for a liquid purification system which is capable of rapidly and accurately sensing the water content of a liquid during purification.

Summary of the Invention

According to a first aspect of the present invention, a water sensing system is capable of being coupled to a liquid to measure the water content of the liquid. The system may produce one or more output signals indicative of the water content of the liquid. The output signals may be used to monitor and control the water content of a liquid. Monitoring and controlling the water content of a liquid may be performed from a location proximal to or removed from the liquid.

According to another aspect of the present invention, a water sensing system for sensing water in a liquid includes a water sensor capable of being coupled to the liquid to produce a first signal having a first value indicative of a water content of the liquid. A processing circuit is coupled to the water sensor and arranged to produce an output

signal in accordance with the relationship between the first value and at least two predetermined threshold values.

According to another aspect of the present invention, a water sensing system for sensing water in a liquid includes a water sensor capable of being coupled to the liquid to produce a first signal having a first value indicative of a water content of the liquid. A processing circuit is coupled to the water sensor and arranged to produce an output signal based on the first value.

According to another aspect of the present invention, a water sensing system for sensing water in a liquid includes a water sensor capable of being coupled to the liquid to produce a first signal having a first value indicative of a relative water content of the liquid. A temperature sensor is capable of being coupled to the liquid to produce a second signal having a second value indicative of a temperature of the liquid. A processing circuit is coupled to the water sensor and the temperature sensor to produce a third signal in response to the first and second signals having a third value indicative of an absolute water content of the liquid.

According to another aspect of the present invention, a liquid purification system for sensing and removing water from a liquid includes a water sensor capable of being coupled to the liquid to produce a first signal having a first value indicative of a water content of the liquid. A processing circuit is coupled to the water sensor to produce an output signal. A purifier is coupled to the processing circuit to remove water from the liquid in response to the output signal.

According to another aspect of the present invention, a method for sensing water in a liquid includes sensing a relative water content value of the liquid, sensing a temperature of the liquid, and electronically converting the relative water content value to an absolute water content value. Electronically converting the relative water content value to an absolute water content value may comprise using a look-up table, or other electronic means, such as an electronically implemented algorithm.

According to another aspect of the present invention, a method for removing water from a liquid includes sensing a water content of the liquid, producing a signal indicative of the water content, and actuating a purifier to remove water from the liquid in response to the signal indicative of the water content.

According to another aspect of the present invention, a method for calibrating a water sensor includes measuring the water content of a first medium having a first known water content value using a water sensor probe to produce a first output signal, measuring the water content of a second medium having a second known water content value using the water sensor probe to produce a second output signal, and electronically calibrating the water sensor using the first and second known water content values and the first and second output signals.

According to another aspect of the present invention, a method for calibrating a temperature sensor used in a water sensing system includes measuring the temperature of a temperature sensor probe using an external device, and electronically calibrating the temperature sensor using the temperature measured by the external device.

Brief Description of the Drawings

Figure 1 is a block diagram of a water sensing system according to an embodiment of the present invention.

Figure 2 is detailed block diagram of a water sensing system according to another embodiment of the present invention.

Figure 3 is a detailed partial block/partial circuit diagram of a water sensing system according to the embodiment of Figure 2.

Figure 3a is a partial block/partial circuit diagram of a light intensity control circuit according to an embodiment of the present invention.

Figure 3b is a perspective view of a housing according to the embodiment of Figure 3.

Figure 4 is a block diagram of a water sensing system according to another embodiment of the present invention.

Figure 5 is a frontal view of a display of a water sensing system according to an embodiment of the present invention.

Figure 6 is a partial block/partial circuit diagram of a noise isolation subcircuit according to an embodiment of the present invention.

Figure 7a is a timing diagram illustrating a digital input signal of a noise isolation

circuit according to an embodiment of the present invention.

Figure 7b is a timing diagram illustrating another digital input signal of a noise isolation subcircuit according to an embodiment of the present invention.

Figure 7c is a timing diagram illustrating an intermediate signal of a noise isolation subcircuit according to an embodiment of the present invention.

Figure 7d is a graph of an output signal versus time according to an embodiment of the present invention.

Figure 8 is a block diagram of a water sensing system according to another embodiment of the present invention.

Figure 9 is a detailed partial block/partial circuit diagram of the embodiment of Figure 8.

Figure 10 is a frontal view of a display and a block diagram of a water sensing system according to the embodiment of Figure 9.

Figure 11 is a block diagram of a water sensing system including calibration circuitry according to an embodiment of the present invention.

Figure 12 is a flow chart of a water content calibration program according to an embodiment of the present invention.

Figure 13 is a flow chart of a temperature calibration program according to an embodiment of the present invention.

Figure 14 is a block diagram of a liquid purification system according to another embodiment of the present invention.

Detailed Description of the Preferred Embodiments

One example of a water sensing system embodying the present invention is illustrated in Figure 1 and generally comprises a water sensor 2, a temperature sensor 4, and a processing circuit 5. The water sensor 2, the temperature sensor 4, and the processing circuit 5 cooperate to measure the water content and the temperature of a liquid. The system illustrated in Figure 1 may measure relative water content of a liquid, the absolute water content of a liquid, or both.

The sensors 2 and 4 are also preferably capable of operating in extreme environments. For example, both the water sensor 2 and the temperature sensor 4 are

preferably capable of being immersed in a liquid without malfunctioning. The sensors 2 and 4 are preferably corrosion resistant and capable of withstanding extreme differences in temperature. For example, for power transformer applications, the sensors 2 and 4 are preferably capable of measuring the water content and temperature of transformer oil when a transformer is operating and the oil is at an elevated temperature, and when the transformer is not operating and the oil is at a low temperature. The range of operating temperatures may be extreme if the transformer is located in a low temperature environment. Additionally, the internal electronics of the sensors 2 and 4 are preferably sealed from the liquid being sensed in accordance with the relevant hazard classification/NEMA rating.

The water sensor 2 comprises a probe and internal circuitry associated with the probe to produce a signal indicative of the water content of a liquid. In one embodiment, the water sensor 2 comprises a capacitive probe that produces a voltage indicative of the %RH of the liquid based on the capacitance between interdigitized electrodes of the probe. Alternatively, the water sensor 2 may comprise a resistive probe that measures the water content of a liquid based on the AC resistance of the probe. Any type of water sensor with one or more of the above-described characteristics is within the scope of the invention.

The temperature sensor 4 also comprises a probe and excitation circuitry associated with the probe to measure the temperature of a liquid. In a preferred embodiment, the temperature sensor 4 comprises a resistance temperature difference (RTD) sensor and associated excitation circuitry. An RTD sensor comprises a material, such as platinum. The resistance of platinum changes in response to a temperature change. The excitation circuitry produces a current through the material. The sensor output may be the voltage across the material, which changes as the resistance changes. Alternatively, the temperature sensor 4 may comprise a thermocouple. Any type of temperature sensor with one or more of the above-described characteristics is within the scope of the invention.

In a preferred embodiment, the water sensor 2 and the temperature sensor 4 are located in the same probe. Locating the water sensor 2 and the temperature sensor 4 in the same probe is preferred because the water content and the temperature can be

measured from the same location in a liquid. However, the present invention is not limited to a water sensor and a temperature sensor located in the same probe. For example, the water sensor 2 and the temperature sensor 4 may be located in separate probes. In addition, excitation circuitry associated with the water sensor and the temperature sensor may be located remotely from the probe, e.g., in a computer that monitors the outputs from the sensors 2 and 4.

Although the illustrated embodiment includes a single water sensor 2 and a single temperature sensor 4, multiple sensors may be included and are within the scope of the invention. For example, a plurality of water and temperature sensors may produce a plurality of output signals indicative of the water content and temperature of the liquid. Using a plurality of sensors provides redundancy, which increases reliability. The output signals from the plurality of sensors may be processed to eliminate errors due to one or more faulty measurements. For example, analog to digital conversion circuitry may be coupled to the output of each sensor, which may in turn be coupled to voter logic to select a water content value on which two or more sensors agree.

Another embodiment of a water sensing system may include a plurality of water sensors and temperature sensors coupled to a single fluid system or a plurality of fluid systems. For example, a plurality of water sensors 2 and temperature sensors 4 may be coupled to a single fluid system to measure the water content and temperature of a liquid, e.g., a hydraulic fluid, at a plurality of locations in the fluid system. The output signals from the sensors may be processed in any suitable manner for communicating water content information from the various locations. In a preferred embodiment, the output signals from the plurality of sensors are multiplexed to enable a single processing circuit to process outputs from the plurality of water sensors. In an alternative embodiment, each of the plurality of sensors may include its own processing circuitry to increase processing speed and provide redundancy.

The processing circuit 5 may perform various functions, such as comparison, temperature compensation, calibration, noise isolation, voltage conversion, and output control. In order to perform these functions, the processing circuit 5 may comprise a plurality of subcircuits. For example, the processing circuit 5 may comprise an output subcircuit to drive one or more output devices, a comparison subcircuit to set threshold

values and compare sensed data to the thresholds, a noise isolation subcircuit to prevent coupling of electrical noise to external devices, a temperature compensation subcircuit to perform temperature compensation for %RH measurements, a calibration subcircuit to electronically calibrate the water sensor 2 and the temperature sensor 4, and a voltage conversion circuit for converting the output voltage from the water sensor 2 into %RH values. The processing circuit 5 may include various combinations of subcircuits according to a desired application.

Exemplary types of liquids in which the water sensing system of Figure 1 may be used to sense the water content include oils, such as transformer oil, lubricating oil, hydraulic fluid, gasoline, kerosene, transmission fluid, diesel fuel, and fuel oil. One particular class of hydraulic fluids in which embodiments of the present invention may be used to determine water content is water glycols, such as water ethylene glycols. In addition, embodiments of the present invention may be used to determine water content in other types of liquids, including, for example, the water content in liquid hydrocarbons such as liquid propane.

Another example of a water sensing system is shown in Figure 2. In the illustrated embodiment, the water sensing system includes a water sensor 2, a temperature sensor 4, and a processing circuit 5. The water sensor 2 and the temperature sensor 4 may comprise any of the sensors previously described. The processing circuit 5 includes a temperature compensation subcircuit 6, a comparison subcircuit 7, and an output subcircuit 8.

The temperature compensation subcircuit 6 may perform temperature compensation for %RH measurements to account for the temperature dependency of %RH and/or to allow conversion between %RH and absolute water content or vice versa. For example, the temperature compensation subcircuit 6 may convert the output of the sensor 2 from relative water content, e.g., in %RH to absolute water content, e.g., in parts per million (ppm). The conversion may be effected directly by sensing the temperature, sensing the %RH, converting the %RH value to a ppm value using any suitable means, for example, a look-up table or a temperature compensation algorithm, and displaying the absolute water content value. The term "look-up table" is not limited to data arranged in a tabular format. For example, the term "look-up table" may include

one or more computer databases which include temperature compensation data. In another alternative, temperature compensation may be performed indirectly by measuring %RH and temperature, varying one or more threshold values with which the %RH value is compared based on the temperature.

In order to qualify various levels of water content, the comparison subcircuit 7 stores one or more threshold values and compares the sensed water content values to the threshold values. For example, if the water content of the liquid is above a predetermined threshold, the comparison subcircuit may produce a high output signal, and if the water content is below a predetermined threshold, the comparison subcircuit may produce a low output signal, or vice versa. Alternatively, the comparison subcircuit may be omitted and the output from the sensors may be displayed directly in analog format, digital format, or both.

The output subcircuit 8 communicates water content information to external devices based on the output from the comparison subcircuit 7. In some embodiments, the output subcircuits may receive external inputs, for example, from a computer to allow the sensing system to interface with the computer. The output subcircuit 8 may produce audible, visible, or a combination of audible and visible output information to the sensor operator. For example, the output subcircuit 8 may produce a signal which drives a visual display, which displays water content, temperature, or both to the operator. The output subcircuit 8 may produce a signal which drives a strip chart recorder, or an alarm, which indicates that the water content of the liquid is above an acceptable level. The output subcircuit 8 may include a computer interface which allows the operator to view and analyze the water content of the liquid. The output subcircuit 8 may also produce a signal which controls one or more external devices 10, e.g., relays, pumps, filters, purifiers, heaters, and/or dryers to remove water or other contaminants from the liquid.

Figure 3 is a detailed partial block/partial circuit diagram of a water sensing system according to the embodiment of Figure 2. In the illustrated embodiment, the water sensor 2 outputs a voltage proportional to the %RH of the liquid. The comparison subcircuit may comprise a pair of potentiometers 3, 3' to set threshold voltages, V_{T1} and V_{T2}, to compare with the water sensor output voltage.

Using potentiometers allows the threshold voltage values to be varied and allows the system to be adapted to sense water in different types of liquids. However, the present invention is not limited to using potentiometers to set the threshold voltages. For example, in a preferred embodiment, the potentiometers may be replaced by a microprocessor, and the threshold voltages may be programmable, e.g., using software or hardware. In still another alternative embodiment, if the water sensing system is designed for use in a known single type of liquid, the threshold voltages may be fixed using resistors having a predetermined fixed value.

In the present embodiment, the threshold voltages V_{T1} and V_{T2} are preferably initially set according to the liquid type and according to a baseline operating temperature of the liquid. For example, V_{T1} and V_{T2} may define lower and upper threshold water content values for a specified type of liquid at its average operating temperature.

Although the illustrated embodiment depicts two threshold voltages, more or fewer than two threshold voltages are within the scope of the present invention. For example, a single threshold voltage may be used to define a single water content threshold. In an embodiment including a single water content threshold, when the water content of the liquid is above the threshold, the sensing system may activate an alarm or other external device, e.g., a purifier. Alternatively, when the water content is above the threshold, the sensing system may deactuate an external device using the water-containing liquid to prevent damage to the device. If only a single threshold voltage is used, it may be preferable to include a timer. The timer may be used to delay the deactivation of the alarm or other external device for a period of time after the transition from upper to lower water content values. However, in an even more preferred embodiment, the sensor circuit includes at least two threshold voltages to provide a hysteresis between upper and lower water content values.

The two threshold voltages used in the present embodiment define three ranges of water content values for a liquid. For example, one range, e.g., a low range, may be defined for water sensor output voltages from about 0V to about V_{T1}. Another range, e.g., an intermediate range, may be defined for water sensor output voltages greater than or equal to about V_{T1} and less than about V_{T2}. Yet another range, e.g., a high range, may be defined for sensor output voltages greater than or equal to about V_{T2}.

In the present embodiment, the low range represents a lower range of water content values for which purification, i.e., removal of water from the liquid, may not be required. The intermediate range represents an intermediate range of water content values for which purification may or may not be required depending on the previous range, as will be discussed below. The high range represents a high range of water content values for which purification may be required.

In addition to representing an intermediate range of water content values, the intermediate range provides a hysteresis between the high and low ranges. For example, V_{T1} preferably defines the low/intermediate threshold below which the sensing system deactuates an external water removal device, such as a purifier. V_{T2} preferably defines an intermediate/high threshold above which the sensing system actuates the external water-removal device. If V_{T1} is equal to or close to V_{T2}, the external water-removal device may oscillate frequently between ON and OFF states, which is undesirable because it wastes energy and stresses mechanical components of the external water-removal device. Accordingly, V_{T2} is preferably set somewhat higher than V_{T1} to define a hysteresis between the high and low water content ranges and reduce the likelihood of frequent oscillation between ON and OFF states.

The comparison subcircuit according to the illustrated embodiment includes voltage comparators 9 and 9' to compare the output from the water sensor 2 to the threshold voltages V_{T1} and V_{T2}. The comparator 9 produces a LOW output signal when the output V_{sens} from the water sensor 2 is greater than or equal to about V_{T1} and a HIGH output signal when V_{sens} is less than about V_{T1}. The comparator 9' produces a LOW output signal when V_{sens} is greater than or equal to about V_{T2} and a HIGH output signal when V_{sens} is less than about V_{T2}. The output signals from the comparators may be used directly to communicate water content information to the operator. However, in the present embodiment, the output signals from the comparators are further processed by an output subcircuit, as will be discussed below.

In a preferred embodiment, the comparators are replaced by a microprocessor and the comparison function is implemented using software. For example, a microprocessor may include an analog to digital converter that converts the output voltage from the sensor to a digital value. A comparison routine compares the digital value to threshold

values set in software. The microprocessor produces one or more output signals based on the comparison.

The temperature compensation subcircuit 6 comprises any type of circuit or algorithm to compensate for the temperature dependency of %RH measurements. In a preferred embodiment, the temperature compensation subcircuit is implemented in software. The temperature compensation subcircuit according to the illustrated embodiment performs temperature compensation indirectly by adjusting the threshold values V_{T1} and V_{T2} when the temperature of the liquid varies from a baseline temperature at which the threshold values V_{T1} and V_{T2} are initially set.

Because the %RH of a liquid increases with decreasing temperature, the temperature compensation subcircuit preferably decreases the threshold values V_{T1} and V_{T2} when the temperature of the liquid increases above the baseline temperature. Similarly, when the temperature of the liquid falls below the baseline temperature, the temperature compensation subcircuit preferably increases the threshold values V_{T1} and V_{T2}. The amount of increase or decrease of the threshold values in response to temperature changes depends on factors such as the type of liquid and the additive content of the liquid. In order to determine the amount of increase or decrease of the threshold values, conventional laboratory methods for determining absolute water content, such as Karl Fischer titration, may be used. Absolute water content data obtained using laboratory methods can be interpolated to generate a look-up table or an algorithm to be used for adjusting the threshold values.

In a preferred embodiment, the look-up table or algorithm which adjusts the threshold values is stored in a memory and accessed by a microprocessor implementing the temperature compensation program. The temperature compensation program reads the output from the temperature sensor 2 and adjusts the threshold values based on the liquid temperature, as described above. The present invention is not limited to using a temperature compensation program. In an alternative embodiment, the look-up table or temperature compensation algorithm may be implemented by an analog circuit or a logic array that calculates the amount of adjustment of the threshold values.

The temperature compensation subcircuit may be configured to vary the threshold voltages for a single liquid type. Alternatively, the temperature compensation subcircuit

may be configured to vary the threshold voltages for a plurality of liquid types. In embodiments configured for multiple liquid types, the system may include an external switch to allow the operator to select a liquid type. In a preferred embodiment, the temperature compensation subcircuit is programmable so that the sensing system can be adapted to perform temperature compensation for any liquid type. By varying V_{T1} and V_{T2}, the aforementioned problem of temperature dependency of %RH measurements may be attenuated.

The output subcircuit of the present embodiment communicates water content information to an operator. An output subcircuit according the present embodiment may be variously configured. For example, in the illustrated embodiment, the output subcircuit comprises a logic subcircuit 12. The logic subcircuit 12 receives the outputs from the comparators 9, 9' and produces control signals C1-C3. If both of the inputs to the logic subcircuit 12 are LOW, the control signal C1 is HIGH. If the output from comparator 9 is LOW and the output from comparator 9' is HIGH, the control signal C2 is HIGH. If the output from comparator 9 is HIGH and the output from comparator 9' is HIGH, the control signal C3 is HIGH. In a preferred embodiment, the logic subcircuit comprises a decoder. Because the control signals C1-C3 are produced by separate outputs from the decoder 12, none of the control signals will be HIGH at the same time.

Although the control signals C1-C3 may be used directly to communicate water content information, the output subcircuit according to the present embodiment preferably further comprises one or more drivers to drive one or more display devices. For example, in the illustrated embodiment the output subcircuit includes a driver 14 coupled to a plurality of lights to visually display water content data to an operator. The driver 14 may comprise a lamp driver or an LED driver, depending on the type of lights used to indicate water content levels.

In operation, when the water sensor output voltage V_{sens} is less than both V_{T1} and V_{T2}, the outputs from both comparators are HIGH and the control signal C3 is HIGH. Since the sensor output voltage V_{sens} is less than both threshold voltages, the water content of the liquid is in the low range. Accordingly, when the control signal C3 is HIGH, the driver 14 actuates a light, preferably a green light 20. The green light 20

may comprise an incandescent lamp or an LED. In a preferred embodiment, the green light 20 comprises an LED.

When the water sensor output voltage is between V_{T1} and V_{T2}, the output from the comparator 9 is LOW, the output from the comparator 9' is HIGH, and the control signal C2 is HIGH. Since the water sensor output voltage is between the threshold voltages, the water content of the liquid is in the intermediate range. Accordingly, when the control signal C2 is HIGH, the driver 14 actuates another light, preferably a yellow light 18. The yellow light may comprise an incandescent lamp or an LED. In a preferred embodiment, the yellow light comprises an LED.

When the water sensor output voltage is greater than both V_{T1} and V_{T2}, the output from both comparators is LOW and the control signal C1 is HIGH. Since the water sensor output voltage is greater than both threshold voltages, the water content of the liquid is in the high range. Accordingly, when the control signal C1 is HIGH, the driver 14 actuates yet another light, preferably a red light 16. In a preferred embodiment, the red light 16 may comprises an LED.

The following truth table illustrates the relationship between the signals:

	A	B	C1	C2	C3
Low Range	1	1	0	0	1
Intermediate Range	0	1	0	1	0
High Range	0	0	1	0	0

where A and B are the outputs from the comparators 9, 9', respectively.

The green, yellow, and red lights visually communicate water content information to an operator in a manner that facilitates interpretation of the water content of a liquid. Using familiar colors to display water content also reduces the likelihood of interpretation errors and increases the efficiency with which sensing may be performed. However, the present invention is not limited to colors or even to visual displays. For example, water content information may be conveyed numerically using a display screen or audibly using an alarm.

In addition to providing visual output, the output subcircuit may control one or more external devices. For example, in the illustrated embodiment, the output subcircuit controls a relay, which may be used to actuate and deactuate an external device such as a purifier. In one embodiment, the relay may be controlled exclusively by the control

signals C1-C3, which are indicative of the water content of a liquid. Alternatively, the output subcircuit may include a timer subcircuit 31 which controls the relay to operate a purifier for a set period then deactuates the purifier. In a preferred embodiment, the relay is controlled by a combination of the control signals C1-C3 and the timer 31.

In order to allow the control signals C1-C3 to influence the operation of the relay and to provide the hysteresis between the high and low water content ranges, the output subcircuit preferably further comprises an S/R flip-flop 24. The control signal C1 is connected to the SET input of the S/R flip-flop 24 to set the output Q of the flip-flop 24 when the water content of a liquid is in the high range. The control signal C3 is connected to the RESET input of the flip-flop 24 to reset the output Q when the water content of the liquid is in the low range.

The output Q of the flip-flop 24 may be used to actuate and deactuate an external device directly. For example, in an embodiment without a timer subcircuit, when the output Q becomes HIGH, the water content is in the high range, and the relay actuates an external device. When the output Q becomes LOW, the water content is in the low range, and the relay deactuates the external device.

Since the control signal C2 is not connected to the flip-flop 24, the output Q of the flip-flop 24 does not change when the water content enters the intermediate range. More particularly, when the water content transitions from the high range to the intermediate range, the output Q of the flip-flop 24 remains HIGH. When the water content changes from the low range to the intermediate range, the output Q of the flip-flop 24 remains LOW. In this manner, the flip-flop 24 provides a hysteresis between the high and low water content ranges.

Operating an external device based solely on water content may be desirable in some instances in which water is the only impurity to be removed from a liquid. However, it may be desirable to remove other impurities, such as particulate contaminants from the liquid. Particulate contaminants may be removed by filtering the liquid before or after the liquid enters a purifier, for example, by passing the liquid through a filter upstream or downstream of the purifier. Since the time required to reduce particulate contaminants to an acceptable level may not be equal to the time required to reduce water content to an acceptable level, the output subcircuit preferably

includes an OR gate 26 to OR the output from the S/R flip-flop 24 with the output from the timer 31.

The timer subcircuit is preferably configured to produce a HIGH output signal as the timer counts down a predetermined time period and a LOW output signal before the count begins and after the predetermined time period expires. Producing a HIGH output signal forces the output of the OR gate 26 to be HIGH regardless of the output of the flip-flop 24. Thus, during the predetermined time period while the counter is counting down, an external device remains actuated regardless of the water content of the liquid. If the timer expires, the output of the OR gate becomes LOW and an external device is controlled by the output Q of the flip-flop 24.

The predetermined time period may be varied according to a desired level of purification; i.e., the time period may be increased if the application requires cleaner liquid. In addition, the predetermined time period may be varied automatically. For example, the present invention may include a sensor for sensing particulate contamination in a liquid. The sensor may be coupled to the timer to vary the time period according to the particulate contaminant level. A start/reset signal may be provided to the timer by the sensor circuit or by the external device.

Although the illustrated embodiment depicts the output subcircuit as implemented by hardware components, the present invention is not so limited. In a preferred embodiment, some or all of the components of the output circuit are implemented using software. For example, the timer circuit, the S/R flip-flop, and the decoder may be omitted and the output signals may be controlled by an output control program.

The relay according to the present embodiment may be variously configured. For example, in the illustrated embodiment, the relay comprises a coil 30 and a switch 32. A relay driver 28 is included to control the position of the switch. An external device such as a purifier may be connected in series with one of the terminals of the switch. The relay may, for example, control an external relay or switch which supplies operational power to the external device.

In the illustrated embodiment, the switch is shown in the OFF position. When the output D1 of the OR gate is HIGH, the relay driver energizes the coil which changes the switch to the ON position. Accordingly, a device connected in series with the

normally open (N.O.) terminal of the relay may be supplied with operational power. When the output of the OR gate is LOW, the switch changes to the OFF position and deactuates an external device.

In order to provide an indication of the position of the switch during operation of the sensing system, the output subcircuit preferably further comprises a switch position indicator light 22. In a preferred embodiment, the switch position indicator light 22 produces a color, preferably not red, yellow, or green, e.g., white. The light 22 may comprise an incandescent lamp or an LED. In a preferred embodiment, the lamp 22 comprises an LED. The light 22 is controlled by the output D1 of the OR gate 26. When D1 is HIGH, the switch is in the N.O. position, and the light 22 is ON. When D1 is LOW, the switch is in the N.C. position, and the light 22 is OFF.

Providing a visual indication of the relay position may be useful when the position is not evident from the operation or non-operation of an external device. For example, if the sensing system is coupled to a liquid and not to an external device and the water content is in the intermediate range, the relay may be closed or open, depending on whether the previous range was low or high. Absent some external indicator, the position of the switch may not be known. Accordingly, the light 22 provides a visual indication of the position of the relay which may otherwise be unknown.

Although the illustrated embodiment includes a single relay, the present invention is not limited to such an embodiment. For example, another embodiment of the present invention may include two or more relays to control a plurality of external devices. Any number of relays is within the scope of the invention.

In addition to controlling one or more relays and providing visual outputs, the output subcircuit may directly interface with an external device, such as a programmable logic controller or a computer. Accordingly, the output circuit may include one or more drivers or regulators for converting the outputs from the sensors into a format suitable for interfacing with the external device. For example, the output subcircuit may include one or more regulators to interface with a programmable logic controller that includes a standard 4-20 mA interface. The output circuit may also include one or more analog to digital converters for interfacing with an external microprocessor. Moreover, in embodiments in which the output subcircuit drives an external device, e.g., a purifier,

the output subcircuit preferably provides an indication of the operating state of the external device. For example, if the output subcircuit controls a purifier and also includes a computer interface, the output subcircuit preferably transmits the operating state, i.e., ON or OFF, of the purifier to the computer. The output subcircuit may also transmit the water content information, for example, %RH, absolute water content, or both, to the computer.

The water sensing system preferably includes a power supply 34 to convert AC line voltages to voltages usable by the device. The power supply 34 may be part of the sensor circuit or a separate component. The power supply 34 may be variously configured. In a preferred embodiment, the power supply is configured to automatically convert 115 V, 60 Hz, 220 V 60 Hz, and 240 V, 50 Hz signals to the appropriate DC levels, e.g., +5 V DC for logic devices. This feature allows the device to work under both U.S. and European power systems without requiring an external switch. Alternatively, the water sensing system may include an internal power source, such as a battery.

According to a further aspect, the output subcircuit may include a light intensity control circuit 36 to control the power supplied to the lights to control the luminous intensity of the lights. Features of the light intensity control circuit are discussed below. The light intensity control circuit preferably includes a potentiometer or other power adjustment device to allow an operator to adjust the luminous intensity of the lights according to the lighting conditions of an operating environment.

In a preferred embodiment, the water sensing system preferably maintains a substantially constant average or perceived luminous intensity of the indicator lights and other lights used to display water content information, even when the power supply voltage varies. For example, when the water sensing system is connected to external AC power systems, the line voltage input to the power supply may vary from about 90 VAC to about 250 VAC. In addition, power surges or interruptions in a power supply system may cause the voltage supplied to the water sensing system to vary. This line voltage may be rectified and used to power indicator LED's and LED's used in segmented displays that display water content and temperature information. Because the luminous intensity of LED display devices varies with applied current, preferred embodiments of

the present invention include an LED intensity control circuit for maintaining a substantially constant average current through the LED's by switching the LED's on and off.

Figure 3a illustrates an example of a light intensity control circuit according to a preferred embodiment of the present invention. In the illustrated embodiment, a transformer T1 and a bridge circuit B1 convert AC line voltage from an external power source into an unregulated 7-30 VDC voltage. For example, when the external line voltage is about 90 VAC, the signal is about 7 VDC. When the external line voltage is 250 VAC, the signal is about 30 VDC. If the 7-30 Volt unregulated DC voltage were used directly to power the LED's, the intensity of the LED's D_1-D_n would vary when the water sensing system is connected to different power systems. Accordingly, in order for the water sensing system to provide uniform luminous intensity, a microcontroller U1 calculates and controls the duty cycle of an LED driver control signal C_1 to maintain a substantially constant average current through the LED's by switching the LED's on and off.

In a preferred embodiment, the microcontroller U1 comprises a Motorola 68HC11. The 68HC11 microcontroller includes an internal A/D converter and internal memory devices. A voltage divider circuit comprising resistors R_1 and R_2 divides the unregulated 7-30 VDC signal into a level suitable for input to the A/D converter of the microcontroller U1. The present invention is not limited to the 68HC11 processor. For example, another microcontroller with an external A/D converter and external memory circuits is within the scope of the invention.

A duty cycle calculation algorithm stored in the memory of the microcontroller U1 calculates required duty cycle to maintain a constant average luminous intensity of the LED's in response to the input to the A/D converter. When the line voltage decreases, the algorithm increases the duty cycle. When the line voltage decreases, the algorithm decreases the duty cycle. As a result, a substantially constant average luminance intensity is maintained. In a preferred embodiment, the relationship between the duty cycle and the unregulated DC voltage is linear. For example, the duty cycle may be inversely proportional to the unregulated DC voltage. One approximation for the duty cycle may be:

$$\text{Duty Cycle} = 7\ \text{VDC}/V_{unreg} \qquad (1),$$

where V_{unreg} is the unregulated DC voltage. For example, when the unregulated DC voltage is low, e.g., about 7 VDC, the duty cycle is high, e.g., about 100%, according to the approximation. When the unregulated DC voltage is high, e.g., about 30 VDC, the duty cycle is low, e.g., about 23%, according to the approximation. In other words, according to the approximation, the product of the duty cycle of the signal C1 and the unregulated line voltage is maintained substantially constant.

An LED driver IC 500 receives the signal C1 and controls the current through the LED's by switching the diodes on and off in response to the duty cycle of the signal C1. The switching frequency of the diodes is preferably selected such that the switching is undetectable by the human eye. In a preferred embodiment, the switching frequency is at least about 100 cycles per second, and more preferably at least about 200 cycles per second.

The LED driver IC 500 may be variously configured. In a preferred embodiment, the LED driver IC comprises a plurality of serial-in/ parallel-out shift registers. The number of outputs of the shift registers corresponds to the number of LED's. The duty cycle of the signal C1 controls the switching of all of the outputs.

More particularly, in the illustrated embodiment, each LED is connected in series with a 300 Ohm resistor R_3-R_n. Each 300 Ohm resistor R_3-R_n is connected to the unregulated 7-30 VDC node. The forward voltage drop across each of the LED's when the LED's are on is about 2 V. The current through one of the diodes is given by the following expression:

$$I_{avg} = \left(\frac{V_{unreg} - V_f}{R_3}\right) * D$$

where D is the duty cycle of the signal C1.

In a preferred embodiment, the average current through the diodes is maintained to be about 17 mA to maintain a desired average luminous intensity level. For example, in order to maintain a 17 mA average current, when the unregulated voltage is 7 V, the duty cycle of the signal C1 is preferably about 100%. If the voltage V_{unreg} is about 18.5

V, the duty cycle of the signal C1 is about 31% in order to maintain an average current of 17 mA.

The present embodiment is not limited to maintaining a 17 mA average current through the LED's. For example, the circuit may include one or more external controls to allow the operator to vary the duty cycle of the signal C1 to make the diodes appear brighter or dimmer. Alternatively, a potentiometer may be coupled to the LED's to regulate the average current through the LED's.

The present invention is not limited to the light intensity control circuit of Figure 3a. For example, a 7 V regulator may be used to convert the unregulated 7-30 VDC signal into a constant voltage of 7 V to be supplied to the LED-resistor series circuits. This arrangement would result in a substantially constant current through the LED's. However, when the line voltage is greater than 7 V, energy is wasted in the regulator. In contrast, according to the present embodiment, the LED's are switched on and off in response to the power line voltage and the energy loss is negligible. Thus, the present embodiment provides a constant average luminance intensity for the LED's and conserves energy. In yet another alternative embodiment, in which the LED's are replaced by incandescent lamps, the present invention may include an analog or digital circuit for regulating the RMS current for powering the lamps to maintain a substantially constant perceived luminous intensity.

According to a further aspect, the water sensing system preferably includes a housing. The housing comprises any housing suitable for containing and protecting electronic components. In a preferred embodiment, the housing is splash proof to protect the sensor circuit. For example, the housing may substantially conform to the appropriate NEMA specification for the packaging of electronic devices. The housing may comprise a removable lid to allow replacement and repair of the sensor electronics. The lid preferably includes a gasket to reduce the likelihood of liquid entry around the lid. The housing may include an inlet for an AC power cord in embodiments in which the housing receives power from an external AC supply. Alternatively, the housing may include an internal power supply such as a battery. In embodiments which include a battery, the AC power cord may be omitted or included as an additional source of power. The housing further comprises a sensor cable inlet to allow a sensor cable to

communicate with the interior electronics. The housing is preferably portable and may comprise a hand held unit.

In embodiments of the water sensing system that include indicator lights, e.g., as shown in Figure 3, the housing preferably includes a plurality of apertures to accommodate the indicator lights. Figure 3b illustrates an exemplary housing for the water sensing system including indicator lights according to the embodiment of Figure 3. Alternatively, in embodiments of the water sensing system that include an alphanumeric display, the housing may include a window for the display. In still other embodiments, the housing may include both apertures for indicator lights and a window for a display. In another alternative embodiment, the housing may be omitted. For example, the sensing system may comprise a circuit card which plugs directly into an adapter card socket in a PC. In addition to the functional features of the housing, the present invention also includes the ornamental features of the housing, as shown in Figure 3b and described above.

In some applications, measuring %RH of a liquid is useful without performing temperature compensation. For example, where the temperature of a liquid remains stable, measuring %RH may be useful to indicate whether the water content is within an acceptable range. Accordingly, one embodiment of the present invention, as illustrated in Figure 4, includes a sensing system without a temperature compensation subcircuit. The illustrated embodiment includes a water sensor 2, a temperature sensor 4, and a processing circuit 5. The processing circuit 5 includes an output subcircuit 8. The processing circuit 5 may also include a comparison subcircuit as described above in the discussion relating to Figure 3 and a calibration subcircuit. In a preferred embodiment, the processing circuit 5 comprises a microcontroller U1.

The microcontroller U1 processes the output signals from the sensors 2 and 4. For example, the microcontroller may convert the output signals to digital values to be displayed by the output subcircuit. The microcontroller may be programmed to perform temperature compensation. However, in the illustrated embodiment temperature compensation is not included. Although the illustrated embodiment depicts a microcontroller U1, a microprocessor with external memory and support circuitry is within the scope of the invention.

Any of the previously described embodiments of the water sensor 2 and the temperature sensor 4 may be used in the present embodiment. One reason for including a temperature sensor in an embodiment without a temperature compensation subcircuit is to monitor the operating temperature of a liquid. Providing temperature information in addition to water content information allows an operator or external device to determine whether the water content of a liquid is within a safe range for a given temperature. Another advantage of including a temperature sensor is that the operator may measure the operating temperature of the liquid for other reasons, such as preventing overheating or freezing of the liquid.

The output subcircuit 8 may be variously configured. In the illustrated embodiment, the output subcircuit includes a display, first and second analog interface outputs, and a PC interface. The output subcircuit preferably also includes a noise isolation subcircuit to isolate the first and second analog interface outputs from the ground the sensing system. The output subcircuit preferably also includes a light intensity control circuit as illustrated in Figure 3a for controlling the luminous intensity of the numbers of the display.

An exemplary display which may be included in the embodiment of Figure 4 is shown in Figure 5. In the illustrated embodiment, the display is configured to provide %RH and temperature data in decimal format to the operator. For example, the display may comprise a liquid crystal or an LED display device which displays the temperature and the water content to the operator in a digital format. A plurality of toggle switches may be included to toggle the display between %RH, degrees Celsius, and degrees Fahrenheit. Alternatively, the display may have a fixed format which displays temperature and water content simultaneously or only water content. In a fixed screen format, the switches may be omitted. In yet another alternative, the display may comprise a lamp or LED display which indicates when threshold water content values are exceeded, as described with respect to Figure 3.

The present invention is not limited by the type of display. For example, the display may comprise an analog meter including a displacement arm and a preprinted background including temperature and/or water content scales. One or more scales may be included on the background to allow the sensor to display water content with varying

degrees of sensitivity. A switch may be included to switch the display between temperature and water content and between the various scales of water content ranges. Alternatively, the display may include separate analog meters to display water content and temperature simultaneously. In another alternative, the subcircuit may include both analog and digital display outputs.

The personal computer (PC) interface 11 may be any interface suitable for connecting the output subcircuit to a personal computer. For example, the PC interface may comprise an Industry Standard Architecture (ISA) interface, a Personal Computer Memory Card International Association (PCMCIA) interface, or any other PC interface suitable for input/output access by a microcontroller. In a preferred embodiment, the PC interface comprises an RS232 interface. The PC interface allows water content data to be monitored and analyzed by an external computer, such as a lap-top computer.

The analog interface outputs illustrated in Figure 4 may be variously configured. In a preferred embodiment, the output subcircuit includes first and second analog interface outputs A1 and A2 for water content and temperature, respectively. For example, the first analog interface output A1 may regulate a signal in an external device responsive to the measured water content of the liquid. The second analog interface output may regulate a signal in an external device responsive to the measured temperature of the liquid. In a preferred embodiment, the first and second analog interface outputs regulate current in a standard 4-20 mA interface.

A standard 4-20 mA interface includes a power supply and a resistor connected in series. A meter, e.g., a voltmeter, is connected across the resistor to measure the voltage across the resistor and determine the current through the resistor. Two external leads connect the standard 4-20 mA interface to a sensor circuit, such as a water sensing system according to embodiments of the present invention. The sensor circuit regulates the current through the resistor such that the meter reads from 4 mA to 20 mA.

In the present preferred embodiment, the first analog interface output A1 regulates the current in a standard 4-20 mA interface to vary between 4 and 20 mA based on measured water content. For example, when the measured water content is 0 %RH, the first analog interface output A1 regulates the current in a standard 4-20 mA interface to be about 4 mA. When the measured water content is 100 %RH, the first

analog interface output A1 regulates the current in the standard 4-20 mA interface to be about 20 mA. The first analog interface output A1 preferably varies the current in the standard 4-20 mA interface linearly with measured water content when the measured water content is between 0 %RH and 100 %RH.

The second analog interface output A2 preferably regulates the current in the standard 4-20 mA interface to vary between 4 and 20 mA based on measured temperature. For example, when the measured temperature is a minimum value for a liquid in its operating environment, the second analog interface output A2 may regulate the current in the standard 4-20 mA device to be about 4 mA. When the measured temperature is a maximum value for the liquid in its operating environment, the second analog interface output A2 may regulate the current in the standard 4-20 mA device to be about 20 mA. The second analog interface output A2 preferably varies the current in the standard 4-20 mA interface linearly with measured temperature when the temperature is between the minimum and maximum values for a liquid.

Providing first and second analog interface outputs A1 and A2 to regulate current in a standard 4-20 mA interface allows the water sensing system according to the present embodiment to be used with one or more peripheral devices including such an interface, e.g., a programmable logic controller (PLC), a strip chart recorder, or a computer. A 4-20 mA interface is standard in many industrial devices. Thus, the sensing system may interface with devices other than those listed.

When the water sensing system is coupled to external devices that include a standard 4-20 mA interface, electrical noise may be coupled through the ground of the sensing system to the 4-20 mA outputs and to the external devices. The noise may lead to inaccurate water content or temperature readings by the external devices.

The problem of noise increases when the external devices are located remotely from the sensing system due to differences in ground potential. For example, a strip chart recorder may be connected to an electrical outlet in a control room of a plant. A water sensing system may be connected to an outlet on the manufacturing floor to sense water in a lubricating liquid for a machine on the manufacturing floor. The ground potential of the control room outlet may be different from the ground potential of the manufacturing floor outlet, e.g., higher or lower. Because of the difference in potential,

ground currents may flow between the sensing system and the remote device. Accordingly, the present embodiment preferably includes a noise isolation subcircuit which prevents ground currents and other noise from external devices from affecting the analog interface outputs by electrically isolating the analog interface outputs from the ground of the sensing system.

Figure 6 illustrates a noise isolation subcircuit 100 for the water sensor and a microcontroller U1 according to the embodiment of Figure 4. The microcontroller U1 receives an output signal from the water sensor and produces output signals 01 and 02 responsive to the output signal from the water sensor. The noise isolation subcircuit 100 produces an analog signal V_{in} indicative of the water content of the liquid in response to the signals 01 and 02. Although not illustrated, a similar noise isolation subcircuit is preferably included to produce an analog signal indicative of the temperature of the liquid.

In order to provide electrical isolation, the noise isolation subcircuit 100 preferably includes one or more isolation devices that produce a signal at an output terminal of the isolation device which is electrically isolated from an input terminal of the isolation device. For example, the isolation device may comprise an isolation transformer. In a preferred embodiment, the isolation device comprises an optical isolator. In a most preferred embodiment, the noise isolation subcircuit comprises two optical isolators U2, U3.

In the illustrated embodiment, each optical isolator U2, U3 includes a light emitting diode (LED) and a phototransistor to electrically isolate the inputs of each optical isolator from the outputs of each optical isolator. Coupling between the input and the output is established through an optical link rather than an electrical link. A problem with using an optical isolator in a circuit which produces an analog signal is the transfer function of an optical isolator may be nonlinear. Moreover, the transfer function may vary with temperature. Thus, it is difficult to produce an accurate continuous-valued or analog signal in a circuit including optical isolators.

In order to solve this problem, the optical isolators are preferably driven in a digital mode in which pulse width modulation is used to represent the water content values. More particularly, the microcontroller calculates and controls the duty cycle of

the signals 01 and 02 used to drive the optical isolators responsive to the output voltage level of the water sensor 2. Driving the optical isolators in a digital mode reduces the effect of the nonlinearity in the transfer function of the optical isolators because the optical isolators are either on or off.

As illustrated in Figures 7a and 7b, the signal 01 is the digital complement of the signal 02. That is, when the signal 01 is high, the signal 02 is low, and vice versa. The signal 01 drives the optical isolator U2. The signal 02 drives the optical isolator U3. The outputs of the optical isolators U2, U3 are commonly connected to produce a switched signal V1, illustrated in Figure 7c. Driving two optical isolators in complement provides a high switching speed of the signal V1 with negligible power loss.

The present invention is not limited to using two optical isolators to switch an output signal. For example, one optical isolator could be used in combination with a pull-down resistor to switch the output signal. However, such a design would result in a slower switching speed and increased power consumption. Therefore, using two optical isolators is preferred.

The noise isolation subcircuit preferably includes a switch U4 coupled to the commonly-connected outputs of the optical isolators. In a preferred embodiment, the switch comprises a CMOS switch because a CMOS switch accurately switches between 0 V and a reference voltage V_{ref}, with a reduced offset voltage. A reduced offset voltage decreases the power consumption of the noise isolation circuit. Other types of switches are within the scope of the invention. For example, a BJT switch may be used if power consumption is not critical.

In operation, the signal V1 controls the switching of the switch U4. More particularly, when the signal V1 becomes high, and the switch U4 switches to V_{ref}. When the signal V1 becomes low, the switch switches to 0 V. When V1 becomes high again, the switch switches back to V_{ref}.

The noise isolation subcircuit preferably includes a low pass filter to convert the output from the switch U4 into a DC voltage. In the illustrated embodiment, the low pass filter comprises a resistor R2 and a capacitor C1. The values of the resistor R2 and the capacitor C1 are preferably chosen such that the cutoff frequency of the low pass filter is lower than the pulse width modulation frequency. For example, for a pulse

width modulation frequency of about 10 kHz, the cutoff frequency of the filter may be chosen to be about 1 Hz. Choosing the cutoff frequency of the low pass filter to be less than that pulse width modulation frequency provides a smooth output voltage that approximates a DC signal.

Figure 7d illustrates the signal V_{in} output from the low pass filter. In the illustrated embodiment, a slight ripple is shown in the signal V_{in} due to the switching. However, the ripple is exaggerated to illustrate the pulse width modulation of the input signals. If the values of R1 and C1 are chosen correctly, this ripple will be negligible. The following expression illustrates the relationship between the signal V_{in} and the reference voltage V_{ref}:

$$V_{in} = D * V_{ref},$$

where D is the duty cycle of the pulse width modulation of the input signals 01 and 02 calculated by the microcontroller.

The noise isolation subcircuit preferably includes a voltage-to-current converter U5 to regulate the current in an external device responsive to the signal V_{in} from the low pass filter. Two external leads L1 and L2 allow U5 to connect to an analog interface, e.g., a standard 4-20 mA interface I1. A diode D1 prevents damage to the sensing system if an operator connects the leads L1 and L2 to reverse polarity. An output stage transistor Q1 regulates current in the interface I1.

In a preferred embodiment, U5 regulates current in the interface I1 to vary between 4 and 20 mA according to measured water content, as discussed above. The water sensing system preferably includes a similar noise isolation subcircuit to provide an isolated 4-20 mA interface output for temperature. The noise isolation subcircuit of Figure 6 may be used in combination with any of the circuits or subcircuits of the water sensing system of the present invention that produce analog outputs.

Another example of a water sensing system embodying the present invention is shown in Figure 8. Like the above mentioned embodiments, the water sensing system of the present embodiment preferably includes a water sensor 2, a temperature sensor 4 to collect water content and temperature data and a processing circuit 5 having an output subcircuit 8 to provide various signals to external devices. In the illustrated embodiment, the output subcircuit 8 comprises an analog interface output, a display

output, a control output, and an interface connection. Each of the outputs may be variously configured as discussed above.

The water sensing system of Figure 8 preferably includes a temperature compensation subcircuit. However, unlike the temperature compensation subcircuit of Figures 2 and 3, which performs temperature compensation indirectly by adjusting threshold values, the temperature compensation subcircuit of the present embodiment performs temperature compensation directly by converting %RH values to ppm values and displaying the ppm values. The temperature compensation subcircuit receives output signals from the water sensor 2 and the temperature sensor 4. In a preferred embodiment, the output signal from the water sensor 2 is indicative of the %RH of the liquid. Thus, for a given instant in time, the %RH and the temperature of a liquid may be known. Given the %RH, the temperature and the type of liquid, the temperature compensation subcircuit 6 may calculate the water content of the liquid in ppm. For example, in a preferred embodiment, the temperature compensation subcircuit may comprise a memory device which stores a look-up table to convert from %RH to ppm. In an alternative embodiment, the temperature compensation subcircuit may include an analog or digital calculating subcircuit which calculates the ppm value. In another alternative, the temperature compensation subcircuit may comprise a microcontroller programmed to convert the values. Using a microcontroller allows the conversion process to be varied or programmed according to the type of liquid and the additive content of the liquid.

Figure 9 illustrates a detailed partial block/partial circuit diagram of the water sensing system of Figure 8. In Figure 9, the temperature compensation subcircuit comprises an electrically erasable programmable read only memory 52 (EEPROM). The EEPROM stores a look-up table comprising ppm conversion values for one or more liquid types. For example, the EEPROM may store conversion values for a plurality of liquid types in separate memory storage areas. In an embodiment in which the EEPROM stores data for a plurality of liquid types, the sensing system may comprise an external switch to select a liquid type.

The values for the look-up table may be determined by conventional laboratory techniques for measuring absolute water content, such as Karl Fischer titration. For

example, the ppm values for a group of samples of a given liquid can be measured in a lab. The temperature and %RH of the samples can be measured using a %RH sensor and a temperature sensor. The relationship between %RH, ppm, and temperature can be determined graphically. A look-up table or a temperature compensation algorithm may be obtained from the graph.

The temperature compensation subcircuit according to the illustrated embodiment further comprises an analog-to-digital (A/D) converter 54 to convert analog signals from the water sensor 2 and the temperature sensor 4 into digital values which correspond to memory addresses in the look-up table. In embodiments where analog subcircuitry is used to calculate the ppm value, the A/D converter may be omitted.

The temperature compensation subcircuit 6 may further comprise a switch 56 to switch between the output from the water sensor 2 and the temperature sensor 4. The temperature compensation subcircuit may also include a timing and control subcircuit 58 to control the position of the switch. The timing and control subcircuit 58 preferably includes a plurality of inputs which allow the operator to select an output type. For example, the timing and control subcircuit may allow an operator to switch between %RH, temperature, and ppm output. In a preferred embodiment, the A/D converter, the timing and control subcircuit, and the switch may be replaced by a microcontroller which performs equivalent functions. That is, the microcontroller accesses the look-up table to convert from %RH to ppm.

The output subcircuit 8 may be variously configured. For example, the output subcircuit may include one or more relays and one or more interface connections. In the illustrated embodiment, the output subcircuit comprises a digital display comprising a plurality of LED or, alternatively, LCD display devices 60 driven by a plurality of display drivers 62 to communicate %RH, temperature, and ppm values. The output subcircuit may include one or more regulators 64 to receive the signals from the sensors 2, 4 and regulate the current in a standard 4-20 mA interface, as described above. In a preferred embodiment, the water sensing system includes a water content output terminal 66 and a temperature output terminal 67. The output signals from the terminals 66 and 67 may be isolated, for example, using a noise isolation subcircuit similar to the circuit illustrated in Figure 6.

In operation, the present embodiment includes a plurality of operating modes. In a temperature operating mode, the switch 56 is connected to the output from the temperature sensor, and the output subcircuit displays temperature information to an operator. The temperature may displayed in degrees Celsius, degrees Fahrenheit, or both. In a %RH operating mode, the switch 56 is connected to the output from the water sensor, and the output subcircuit displays %RH to the operator. In a ppm operating mode, the switch 56 is alternatingly connected to the output from the water sensor and the output from the temperature sensor by the timing and control circuit to select a %RH value and a temperature value for a particular instant in time. The temperature value and the %RH value are digitized by the A/D converter and used to look up a ppm value in the look-up table in the EEPROM. The ppm value is then displayed to the operator via the output subcircuit.

Figure 10 illustrates an exemplary configuration of a display 60, a sensor probe 200, and a circuit board 205 of the water sensing system of Figure 9. In the illustrated embodiment, the display 60 comprises separate alphanumeric readouts for temperature and water content. Alternatively, as illustrated in Figure 5, a single display may be used to display both temperature and water content. The sensor probe 200 includes both the water sensor 2 and the temperature sensor 4. A cable 201 couples the sensor probe 200 to a circuit board 205 which includes the processing circuit 5 and various subcircuits. The cable is preferably removably coupled to the circuit board 205 for storage and portability. The arrows 206 and 207 indicate outputs for providing temperature and water content information to the display 60 and/or to an external device. The water sensing system preferably also includes a switch 202 to switch the water content portion of the display 60 between %RH and ppm and a switch 203 to switch the temperature portion of the display 60 between Fahrenheit and Centigrade or Celsius. The water sensing system may also include a plurality of liquid type controls 204 to select a type of liquid in which water is being measured.

A water sensing system according to the present embodiment provides reliable water content information even when the temperature of the liquid being sensed varies. By converting from %RH to ppm, the sensing system provides a temperature-independent output which can be used to determine whether or not a water content is

above an acceptable level. For example, if the sensing system produces an output signal indicating a water content of above about 500 ppm, an operator may determine that the water level is too high. By determining a permissible water content based on ppm rather than %RH, the problem of temperature dependency of RH sensor measurements is reduced. Alternatively, under operating conditions where the additive content or the saturation characteristics of a liquid is not known, or when the temperature of the liquid is relatively stable during operation, %RH may provide a more useful measurement of water content.

According to another aspect, the present invention includes a method for determining the saturation level of a liquid, even when the additive content of the liquid is unknown. The additive content of a liquid may vary due to a variety of factors, such as, contamination of the liquid over time or changes in the additive package of the liquid. The additive content affects the saturation level of the liquid. Thus, when the additive content is unknown, determining the saturation level may be difficult. As used herein, the term "saturation level" defines the water content of a liquid in ppm corresponding to 100 %RH.

An exemplary method for determining the saturation level of a liquid according to the present invention generally includes calibrating a water sensing system with a sample of the liquid. For example, if it is desired to measure the water content of hydraulic liquid stored in a particular drum, the method includes sampling a predetermined quantity of the liquid. The present invention is not limited to any particular sample quantity. Thus, for example, the sample quantity may be one liter of the liquid. Next, a water sensing system according to any of the embodiments of the present invention may be used to measure the %RH of the liquid, i.e., by inserting the water sensor probe into the sample.

Once the %RH is measured, a known quantity of water is added to the sample. The quantity of water added is preferably selected to be small enough that the likelihood of saturating the sample is small. The quantity of water added depends on a variety of factors, such as, liquid type, sample volume, and anticipated water content level. For illustration, the quantity of water added may be about one milliliter. The added water is mixed with the sample, preferably until substantially all of the water is dissolved.

Because dissolving water in some liquids, such as oils, may be difficult, it may be preferable to first dissolve the water in an intermediate solvent and then dissolve the water/solvent solution in the sample. The intermediate solvent should be selected not to greatly affect the saturation characteristics of the sample. An exemplary solvent that may be used is an alcohol.

Since the quantity of water added to the sample is known and the volume of the sample is known, the increase in water content in parts per million can be determined. For example, adding one milliliter of water to a one liter sample of the liquid increases the water content of the sample by 1000 ppm.

The next step includes measuring the %RH of the sample after the water is dissolved. Again, this measurement is performed by inserting the water sensor probe into the liquid. Next, the difference between the two measured %RH values is determined. The saturation level may then be determined according to the following equation:

$$ppm(sat) = \frac{(1000ppm) * (100\%)}{RHdelta}, 0\% < RHdelta < 100\% \qquad (2)$$

, where ppm(sat) is the saturation level of the liquid and RHdelta is the difference between the measured %RH values. The value ppm(sat) indicates the maximum amount of water that the liquid can hold in solution in parts per million. The saturation level is a useful measurement in determining whether or not the water content of a liquid is within a safe range. In order to convert %RH values to ppm values, the %RH values may simply be multiplied by the saturation level ppm(sat). For example, if ppm(sat) of liquid is 10,000, and the measured %RH at a given time is 10%, then the absolute water content of the liquid is 1000 ppm.

The present invention is not limited to using equation (2) to calculate the saturation level for a liquid. Any equation for calculating the saturation level based on adding a predetermined quantity of water to a liquid and measuring the change in %RH is within the scope of the invention.

The following assumptions are made in the above described method for determining the saturation level. The first assumption is that the water added to the

sample is fully dissolved. The second assumption is that relationship between ppm and %RH is linear over the measured range. For example, if the water added to the sample saturates the sample, the calculated saturation level would be inaccurate if a linear assumption was made. The third assumption is that the temperature of the sample is constant when the first and second %RH measurements are performed.

The above described method for determining the saturation level of a liquid may be programmed into the memory of any of the embodiments of the water sensing system described herein. In other words, an equation for calculating the saturation level and a routine for obtaining the first and second %RH values, as described above, may be implemented in software. These functions are preferably transparent to the user. Thus, in order to determine the saturation level for a liquid, a user actuates the saturation level calculating routine, e.g., by depressing a ppm key on the housing of the water sensing system. Next, the user obtains a sample of the liquid in which it is desired to measure the water content and inserts the sensor probe into the sample. The volume of the sample may be fixed or variable. If the volume is variable, the user may input the sample volume, e.g., using the increment and decrement controls. The saturation level calculating routine then records the output voltage from the water sensor and stores the value in memory. The user then removes the probe from the sample, dissolves a predetermined quantity of water in the sample, and reinserts the probe into the sample. The quantity of water added may be fixed or variable. If the quantity is variable, the user may input the quantity. The saturation level calculating routine records the second %RH value and calculates the saturation level using an equation, such as equation (1), based on factors such as the sample volume, the volume of water added, and the measured %RH values. The saturation level calculating routine preferably stores the calculated saturation level in memory and uses it to convert %RH values to ppm values. Alternatively, the saturation level calculating routine may display the saturation level to the user and the user may perform the conversions manually.

In this manner, water sensing systems according to embodiments of the present invention are capable of calculating the saturation level of liquid and converting to ppm, even when the additive content of the liquid is unknown. Thus, when the additive

content of a liquid changes due to contaminants that accumulate in the liquid over time, changes in the additive package of the liquid, or any other factor causing the additive content to be unknown, embodiments of the present invention are capable of reliably determining the saturation level. When the additive content of a liquid is expected to vary between batches of the liquid, the calibration is preferably performed for each batch. However, due to the simplicity of the calibration process, calibration may be easily performed in the field by the end user. Once the saturation level is stored, subsequent ppm calculations for a liquid may be automatically performed using the stored value without further calibration, unless the additive content changes.

According to a further aspect, embodiments of the present invention may include a voltage conversion algorithm to convert the output voltage from the water sensor into a water content value. The voltage conversion algorithm may be linear or nonlinear, depending on the relationship between the water sensor output voltage and the %RH. In a preferred embodiment, the voltage conversion algorithm is linear.

The voltage conversion algorithm may be determined by measuring the "actual" water content values of a plurality of liquids using a conventional laboratory method, such as Karl Fischer titration and measuring the water sensor output voltages corresponding to the water content values. Data relating the water sensor output voltages to the water content values is then plotted. A curve-fitting algorithm is used to determine the function or algorithm that best approximates the data. The algorithm is then programmed into the memory of the processing circuit to convert the output voltage of the water sensor into a water content value. Alternatively, the algorithm may also be used to generate any suitable circuit, such as a look-up table or logic circuit, for converting the water sensor output voltages into water content values.

If the voltage conversion algorithm is determined to be nonlinear, the complexity or order of the voltage conversion algorithm depends on factors such as, the desired accuracy of the water content measurement, the available memory, and the speed of the microprocessor of the water sensing system. As desired accuracy, available memory, and processing speed increase, the order of the voltage conversion algorithm may be increased to more closely approximate the measured water content data.

The literature distributed with conventional humidity sensors includes an

algorithm for correcting %RH measurements for minor variations in sensor output voltage caused by temperature changes. For example, for one capacitive sensor, the correcting algorithm is:

$$\%RH_{corrected}=\frac{\%RH}{(1.093-(0.0012*Temp))}$$

, where %RH is the percent relative humidity and temp is the temperature in degrees Fahrenheit. However, this conventional correcting algorithm is designed for use with the conventional linear voltage conversion algorithm for converting sensor output voltages to %RH in air. If the voltage conversion algorithm is determined to be different from the conventional voltage conversion algorithm, the correcting algorithm may also require alteration. For example, if the voltage conversion algorithm is nonlinear, the correcting algorithm may be nonlinear.

According to a further aspect, the present invention includes circuitry and methods for calibrating a water sensing system. Unlike other electronic devices which may require complex external equipment and/or return to the manufacturer for calibration, embodiments of the present invention include internal calibration circuitry which allows an operator to calibrate a water sensing system, preferably on-site and without using complex external calibration equipment.

Figure 11 illustrates a water sensing system including water content and temperature calibration programs. In the illustrated embodiment, the water sensor 2 and the temperature sensor 4 may comprise any of the sensors previously described. The processing circuit 5 comprises a microcontroller U1. The microcontroller preferably includes processing circuitry such as a microprocessor to perform mathematical operations for the input signals from the sensors and to calculate calibration values. The microcontroller also includes a memory M1, preferably divided into read-only and random access portions. In a most preferred embodiment, the memory M1 includes a read only portion, a random access portion, and an electrically erasable programmable read only portion. The read-only portion stores programs, e.g., calibration programs and temperature compensation programs. The random access portion stores values generated during the execution of programs, such as digitized sensor output values. The

electrically erasable programmable portion stores data used by the programs, for example, reference calibration values.

Although the illustrated embodiment depicts a microcontroller including an internal memory, the present invention is not limited to such an embodiment. For example, the microcontroller may be replaced by a microprocessor with external memory chips for the three memory portions. The three memory portions may comprise a single or separate chips.

A control block 61 includes jumpers, switches, and other controls to control the operation of the microcontroller. For example, different combinations of the jumpers or switch positions may be used to actuate different calibration programs. The control block 61 preferably also includes a value selection control to select and store calibration values in the memory M1.

The processing circuit preferably also includes a display 60. In some embodiments, for example, those that display water content and temperature values, the display comprises an alphanumeric display. In other embodiments, for example, those that indicate whether one or more thresholds have been exceeded, the display comprises one or more indicator lamps or LED's without an alphanumeric display. In still other embodiments, the display comprises both an alphanumeric display and indicator LED's. If the display comprises an alphanumeric display, the control block 61 preferably includes a display adjustment control to adjust the displayed value during calibration. The display may also include one or more calibration LED's which communicate calibration status information to an operator during calibration.

The present invention is not limited to using a microcontroller and calibration programs to calibrate the sensor. Analog or digital circuitry which performs the same or equivalent functions are within the scope of the invention. For example, the processing circuit may include one or more analog or digital calibration subcircuits to calibrate the water sensor and/or the temperature sensor. The calibration programs or subcircuits may be combined with any of the previously described embodiments of the water sensing system.

The switches or jumpers for accessing the water content and temperature calibration programs, the display adjustment control (if included), and the value selection

control are preferably internal components of the water sensing system, i.e., the calibration components are on a circuit board within the housing of the water sensing system. In an alternative embodiment, the calibration components may be external. However, because the calibration components are preferably accessed only during calibration, it may be more practical for these components to be internal.

In order to accurately calibrate the water sensor, the water sensor probe is preferably inserted into a medium that accurately provides a known, constant %RH value as a reference point. In a preferred embodiment, two calibration media are used to provide two different reference points for %RH calibration. Exemplary calibration media suitable for %RH calibration include humidity cells in which a saturated salt solution produces a known constant %RH in the air above the salt solution in a closed container. The container includes a connector to allow the insertion of the water sensor probe. According to a preferred embodiment, a calibration cell comprising a saturated salt solution of lithium chloride provides a %RH of 11.3% at 75°F may be used for one of the reference points. A calibration cell including a saturated sodium chloride solution, which provides a %RH of 75.3% at 75°F may be used as another reference point in performing %RH calibration.

The present invention is not limited to the use of calibration cells which comprise lithium chloride solutions, sodium chloride solutions, or saturated salt solutions. Any medium which provides an accurate %RH value may be used with the present invention. In another alternative, the water sensor may be heated to remove substantially all of the water from the sensor probe to provide a %RH of 0%. A %RH of 0% could be used to zero the probe and calibrate the water sensor as described below.

Figure 12 illustrates the operation of the water content calibration program, including steps in which an operator provides input to the program, according to a preferred embodiment of the present invention. To initiate the water content calibration program, a sensor operator sets the appropriate jumpers or switches on the circuit board to a predetermined position to actuate the program stored in the memory for obtaining a first measured value for calibration. Next, the operator places the water sensor probe in a calibration medium to provide a first reference %RH value. For example, the first calibration medium may comprise a lithium chloride calibration cell that provides a %RH

of 11.3% at 75 degrees Fahrenheit. The program causes the %RH and calibration LED's on the display (illustrated in Figures 5 and 11) to flash, indicating that %RH of the calibration medium is not stable. The program may determine stability by analyzing the water sensor output voltage, for example, by measuring variations in the water sensor output voltage.

In embodiments of the water sensing system that include an alphanumeric display, the operator uses the display adjustment controls (illustrated in Figure 11) to adjust a numeric readout on the display to be equal to the known %RH. Providing an alphanumeric display thus allows easy adjustment of the water sensing system for use with any calibration medium. Alternatively, in embodiments without an alphanumeric display, the known %RH for a specific calibration medium is preprogrammed in the memory. In embodiments without an alphanumeric display, the operator preferably selects a calibration medium with a %RH corresponding to the preprogrammed value. Thus, in some embodiments, display adjustment is not required.

When the water sensor output voltage becomes stable, e.g., when the variation in the output voltage is within a predetermined tolerance, the program stops the flashing of the LED's and waits for the operator to store the sensor output voltage and the display value. The operator actuates value select control to enter the %RH value of the medium and the sensor output voltage into the memory device. Alternatively, the program may automatically record the water sensor output voltage when the output becomes stable. The program preferably prevents the operator from storing the first water sensor output voltage until the output voltage is stable.

After the program records the first %RH value and the corresponding water sensor output voltage in the memory, the operator preferably executes another routine for recording a second measured value for calibration. To initiate the second routine, the operator actuates the appropriate jumpers or switches on the circuit board. The operator places the water sensor probe in a second calibration medium with a second known %RH, which is preferably different from the first known %RH. For example, the second calibration medium may comprise a calibration cell including a saturated sodium chloride solution that provides a known %RH of 75.3% at 75 degrees Fahrenheit. The program again causes the calibration LED's to flash until the %RH in

the calibration cell stabilizes.

In embodiments having an alphanumeric display, the operator then uses the display adjustment control to set the number on the display equal to the second known %RH. Alternatively, in embodiments without an alphanumeric display, the second known %RH value is preprogrammed in memory. In embodiments without an alphanumeric display, the operator preferably selects the second calibration medium to correspond to the preprogrammed value.

When the %RH becomes stable, the program stops the flashing of the LED's. The program then waits for the operator to store the second water sensor output voltage and the second display value, which is equal to the second known %RH. When the LED's cease to flash the operator activates the value selection control to store the second known %RH and the second water sensor output voltage in the memory. Alternatively, the program may automatically record the water sensor output voltage when the output becomes stable. The program preferably prevents the operator from storing the second water sensor output voltage until the output voltage is stable.

Once the first and second known %RH values and the corresponding first and second water sensor output voltages are stored in the memory. The program calculates calibration factors and stores the calibration factors in the memory device. Any method for calculating the calibration factors is within the scope of the invention. For example, the program may use statistical analysis, e.g., linear regression analysis, to calculate one or more constants or coefficients to adjust the voltage conversion algorithm that converts water sensor output voltage to %RH. Once the program calculates the calibration factors, the program stores the calibration factors in the memory. After the program stores the calibration factors, the operator preferably verifies the calibration by inserting the probe into both the high and low %RH media and verifies that the display reads the correct value for each medium.

The present invention is not limited to using two %RH measurements to calibrate the water sensor. More or fewer measurements are within the scope of the invention. The present invention preferably uses at least two measurements, e.g., a high measurement and a low measurement, to increase the accuracy of the calibration by calculating high and low calibration factors, from which intermediate calibration factors

may be extrapolated.

According to another aspect, the present invention preferably includes circuitry and methods for temperature calibration, in addition to circuitry and methods for water content calibration. Alternatively, some embodiments of the present invention may include circuitry and methods for water content calibration and not for temperature calibration. Still other embodiments of the present invention may include circuitry and methods for temperature calibration only. In a preferred embodiment including temperature calibration circuitry and methods, temperature calibration is performed by the microcontroller according to a temperature calibration program stored in the memory. Figure 13 is a flow chart illustrating the operation of an embodiment of the temperature calibration program, including steps in which the operator provides input to the program.

In order to perform temperature calibration the operator sets the appropriate jumpers or switches on the circuit board to a predetermined position. The program then waits for the operator to select a unit of measure for temperature calibration, e.g., degrees Celsius or degrees Fahrenheit. Another jumper or switch may be used to select the appropriate unit of measure for temperature calibration. The program then causes the Fahrenheit/Celsius and calibration LED's to flash. The operator places an external temperature measuring device, e.g., a calibrated thermometer, near the probe to measure the temperature of the probe. The operator then adjusts the display adjustment controls on the display to set the display temperature equal to the temperature measured by the external temperature measuring device. When the measured temperature becomes stable, e.g., when variation in the output voltage is within a predetermined tolerance range, the program stops the flashing of the LED's and waits for input from the operator. When the LED's cease flashing, the operator activates the value selection control to store the temperature value and the corresponding temperature sensor output voltage. The program preferably prevents the operator from storing the temperature sensor output voltage until the output becomes stable. The program calculates the temperature calibration factor and stores it in memory. The operator then preferably verifies the temperature calibration by varying the temperature of the probe, e.g., by heating or cooling the probe, reading the temperature from the display, and verifying the display

temperature using the external temperature measuring device.

Although the illustrated temperature calibration program calibrates the temperature sensor using a single temperature measurement, the present invention is not so limited. For example, the temperature calibration program may utilize two or more temperature measurements to perform temperature calibration.

By providing water content and temperature calibration programs, the water sensing system according to embodiments of the present invention reduces the need for complex external calibration equipment. Calibration can be performed on-site at the sensing location and measurement accuracy is increased.

In another embodiment of the water sensing system, the processing circuit may comprise a separate unit from the sensor. For example, the processing circuit may be a portable unit designed to process the outputs from a plurality of sensors. The sensors may be attached to devices using the liquids in which the water content is being sensed. For example, a water sensor may be coupled to the housing of a helicopter transmission to measure the water content of the transmission fluid. The processing circuit may be capable of coupling to the sensor through an inductive or a direct electrical connection to process the output signal from the sensor when the helicopter is on the ground. In this arrangement, the processing circuit is not subjected to the harsh operating environment caused by vibrations and extreme temperatures experienced during flight. A portable processing circuit may also be capable of measuring the water content of liquids in vehicles other than helicopters, for example, in watercraft, or in land vehicles which may produce a harsh operating environment for a processing circuit or which may have power, space, or weight constraints. A portable processing circuit is preferably battery powered to enable use in environments where external power is not available.

In an embodiment in which the sensor probe is separate from the processing circuitry, the housing for the processing circuitry may include a sensor interface to allow the processing circuitry to communicate with an external probe. The sensor interface may comprise a cable, an antenna, or any other means suitable for communications.

In yet another alternative embodiment, the water sensing system, including the processing circuit, the water sensor, and the temperature sensor, may comprise a portable unit. In such a unit, the processing circuit may include any of the subcircuits

previously described, e.g., a comparison subcircuit, a voltage conversion subcircuit, a temperature compensation subcircuit, and/or a calibration subcircuit.

The water sensing system according to the present embodiment is preferably battery-powered to increase portability. In a most preferred embodiment, the water sensing system is powered by a nine Volt non-rechargeable battery. Using a nine Volt non-rechargeable battery is preferred because such batteries are inexpensive and readily available. However, any type of power source suitable for powering the water sensing system is within the scope of the invention. For example, the water sensing system may be powered using a solar cell.

The water sensing system according to the present embodiment preferably also includes a display for displaying water content information. Because the present embodiment is preferably battery-powered, the display is preferably a low power display, such as a liquid crystal display. The display is preferably capable of displaying numbers indicative of the water content and temperature and labels, such as, "%RH", "ppm", "°C" and "°F". However, the present invention is not limited to using a liquid crystal display. Any display suitable for low power operation is within the scope of the invention. For example, the display may comprise an analog meter.

A water sensing system according to any of the embodiments previously described may be used to maintain a desired water content level in a liquid. For example, in hydraulic fluids, such as water glycols, it may be desirable to maintain a ratio of water to glycol. In ethylene glycol/water solutions, the water may evaporate faster than the ethylene glycol. As a result, the ratio of water to ethylene glycol may vary over time. Since the ratio affects properties of the hydraulic fluid, such as boiling point, freezing point, and flame retarding ability, it is desirable to maintain a specified ratio of water to ethylene glycol in some hydraulic systems. Accordingly, any of the embodiments of the water sensing system previously described may be used to sense the water content of a hydraulic fluid and produce an output signal for adding water to the hydraulic fluid. Water may be added automatically by a actuating a valve coupled to a hydraulic fluid system or manually by an operator until the ratio is within a desired range of values.

According to a further aspect of the present invention, a water sensing system according to any of the previously described embodiments may be combined with one

or more external devices such as a purifier to remove water and other contaminants from the liquid. For example, the water sensing system according to Figures 2 and 3 may be coupled to a purifier to provide a liquid purification system controlled by temperature compensated water content threshold values. Alternatively, a water sensing system without a temperature compensation subcircuit, for example, as shown in Figure 4, may be coupled to a purifier to provide a liquid purification system controlled by %RH water content data. In another alternative, a water sensing system capable of switching between temperature compensated data and %RH, for example, as shown in Figures 8-10, may be coupled to a purifier to provide a liquid purification system with both %RH and ppm measurement capability.

A purifier according to the present embodiment can be any type of purifier suitable for removing water from liquids. For example, the purifier may comprise a spinning disk purifier, a nozzle purifier, or a tower purifier. Exemplary spinning disk fluid purifiers suitable for removing water and other contaminants from liquids are disclosed in U.S. Patent No. 4,604,109 to Koslow, entitled "Fluid Purifier", and U.S. Patent No. 5,133,880 to Lundquist et al., entitled "Fluid Purifier and Method for Purifying Fluid Contaminated with a Volatile Contaminant", the disclosures of which are hereby incorporated by reference. A spinning disk fluid purifier suitable for use with the present embodiment includes a fluid housing, at least one spinning disk inside the housing, a fluid inlet, a vapor outlet, and a fluid outlet. In operation, fluid contaminated with water enters the housing through the fluid inlet and contacts at least one of the spinning disks. After contacting a disk, the contaminated fluid is thrown radially outward from the disk in the form of small droplets which travel toward and contact an interior wall of the housing. Water present in the fluid is vaporized during the travel of the droplets and exits the housing through the vapor outlet. The purified droplets coalesce and flow down the interior wall of the housing and exit through the fluid outlet. A particle filter is preferably located upstream of the purifier to remove large particles from the liquid before the liquid enters the purifier. A second filter may be located upstream or downstream of the purifier to remove smaller particles from the fluid.

A tower fluid purifier suitable for use with the present embodiment includes a vacuum tower chamber maintained under a vacuum to remove contaminants, such as

water, from fluids, such as oils. A vacuum pump creates a vacuum that draws contaminated fluid into the purifier. The fluid enters the purifier through an inlet valve and proceeds through a heater. The fluid enters the vacuum tower chamber through an inlet at the top of the vacuum tower chamber. A regulating valve regulates the flow of fluid into the chamber. The fluid flows in a downward direction over a dispersion material inside the chamber. As a result, the surface area per unit volume of the fluid is increased.

Free and dissolved air, liquids, and gases are removed from the fluid by exposing the fluid to a low relative humidity atmosphere which is obtained by maintaining a vacuum in the chamber. The low pressure in the chamber draws ambient air into the chamber. The air enters the purifier through a filter and a restrictor orifice. The air enters the chamber through an air inlet at the bottom of the chamber and proceeds upwards against the falling flow of contaminated fluid. Water and gases are removed from the fluid in the upward air flow and exit at the top of the chamber. An oil mist filter at the top of the chamber separates oil from air. Excess oil is drained from the oil mist filter to the bottom of the chamber. The purified oil collects at the bottom of the chamber. A discharge pump removes the purified oil and returns it to the reservoir or system being purified.

A nozzle fluid purifier suitable for use with the present embodiment includes a vacuum chamber. A spray nozzle located at the top of the vacuum chamber sprays a cone of fluid into the chamber with a thin film and a large surface area. A vacuum pump maintains the vacuum chamber at a predetermined vacuum to optimize purification for a particular application. Air enters the vacuum chamber through a filter and a restrictor. The filter removes contaminants from the air. The restrictor allows expansion of air inside the chamber to about three times the ambient volume of the air. As a result, the relative humidity inside the chamber is about one third of the ambient level.

Gases and water vapor are transferred from the fluid surface to the upward flowing air, thereby drying and degassing the fluid. The air and contaminants exit the chamber through an oil mist separator and to the atmosphere. Purified fluid collects in the bottom of the chamber. A discharge pump returns the purified fluid to the reservoir

or system being purified.

One example of a liquid purification system embodying the present invention is illustrated in Figure 14. According to the illustrated embodiment, the system includes an external device such as a purifier 40 to remove water from the liquid. The purifier 40 may include a control circuit 44 to actuate and deactuate the purifier. A processing circuit 5 is coupled to the control circuit to control the actuation and deactuation of the purifier. The processing circuit 5 may comprise any of the sensor circuits including any of the subcircuits in the previously described embodiments. The processing circuit may be physically incorporated with or separate from the purifier control circuitry. In a preferred embodiment, the processing circuit 5 comprises a portable unit separate from the purifier 40 but capable of communicating with the purifier 40. For example, the embodiment of Figure 3 includes a relay that may control the purifier 40.

In order to sense the water content and temperature of the liquid being purified, the liquid purification system preferably includes a water sensor 2 and a temperature sensor 4. Alternatively, the temperature sensor 4 may be omitted. The sensors 2 and 4 may be coupled to the liquid, e.g., inserted in a liquid reservoir. Alternatively, the sensors 2 and 4 may located in the purifier or coupled to a conduit upstream or downstream of the purifier 40.

In order to filter particulate contaminants from the liquid, the system preferably includes a filter 42. In a preferred embodiment, the filter 42 comprises a 3 μm ($\beta_3 \geq$ 200) Ultipor® filter available from Pall Corporation. The filter 42 may be incorporated with or separate from the purifier. For example, the filter may be located upstream, downstream, or within the purifier 40. In the illustrated embodiment, the filter 42 located downstream from the purifier.

In operation, the purifier may be coupled to a liquid reservoir, e.g., an oil drum, to purify the liquid. The water sensor 2 senses the water content of the liquid. If the water content is above a first predetermined level, e.g., the turn-on level, the processing circuit 5 sends a signal to the control circuit 44 to actuate the purifier 40. The purifier operates until the water content level is below a second predetermined level which is preferably less than the turn-on level to prevent oscillation between ON and OFF states, as discussed in the embodiment of Figure 3. Although using two thresholds is preferred,

actuation and deactuation of the purifier using a single threshold value is within the scope of the invention.

In embodiments in which the processing circuit includes a timer circuit, the purifier may operate to remove particulate contaminants from the liquid even when the water content is below an acceptable level. A timer circuit causes the purifier to operate for a predetermined time period. For example, if the water content is reduced below an acceptable level before the time period expires, the purifier nonetheless continues to operate beyond the time required for water removal in order to remove the particulate contaminants. If the time required for water removal is greater than the predetermined time period, then the purifier may operate beyond the time period for particulate filtration. In this manner, the liquid purification system according the present embodiment reliably removes both water and particulate contaminants from a liquid.

Although the purifier may be actuated and deactuated automatically by signals from the water sensor and/or a timer, as described above, other methods of controlling a purifier using a water sensor are within the scope of the invention. For example, the purifier may be actuated by an operator to begin purification of a liquid. The water sensor 4 may deactuate the purifier when the water content of the liquid is below a predetermined level. In another alternative, the water sensor may actuate the purifier when the water content is above a predetermined level and an operator may deactuate the purifier after a predetermined time period. Alternatively, the water sensor may display the water content to the purifier operator and the operator may actuate or deactuate the purifier according to the indicated level. In embodiments in which the purifier includes a heater to accelerate the purification process, the water sensor may be used to actuate and deactuate the heater when the water content is above or below a predetermined level or levels to save energy. Thus, coupling the water sensor to a purifier in any manner to control the purification process is within the scope of the invention.

A liquid purification system according to the present invention is preferably portable and suitable for on-line, i.e., real time and preferably in-line, sensing of water and purification of liquids. The combination of the sensors, the processing circuit, and the purifier increases the efficiency of the purification system by sensing the water

content of a liquid as the liquid is being purified. The need for performing lab tests such as Karl Fischer titration is reduced. The combination of sensing and purifying makes the present embodiment particularly suitable for operations in which large numbers of separate containers require purification because the time required to purify liquid in each individual container is decreased.

While the invention has been described in some detail by way of illustration and example, it should be understood that the invention is susceptible to various modifications and alternative forms, and is not restricted to the specific embodiments set forth. It should be understood that these specific embodiments are not intended to limit the invention but, on the contrary, the intention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the invention.

What is claimed is:

1. A water sensing system for sensing water in a liquid comprising:

a water sensor capable of being coupled to the liquid to produce a first signal having a first value indicative of a water content of the liquid; and

a processing circuit coupled to the water sensor and arranged to produce an output signal in accordance with the relationship between the first value and at least one predetermined threshold value.

2. The system of claim 1 wherein the processing circuit includes a comparison subcircuit which compares the first value to the predetermined threshold value to produce at least one comparison result.

3. The system of claim 1 further comprising a temperature sensor capable of being coupled to the liquid to produce a second signal having a second value indicative of the temperature of the liquid, the temperature sensor being coupled to the processing circuit.

4. The system of claim 3 wherein the processing circuit is coupled to the temperature sensor to vary the predetermined threshold value in response to the second signal.

5. The system of claim 4 wherein the processing circuit varies the predetermined threshold value and thereby performs temperature compensation.

6. The system of claim 2 wherein the processing circuit stores or generates a first predetermined threshold value and a second predetermined threshold value, the first predetermined threshold value being less than the second predetermined threshold value.

7. The system of claim 6 wherein the comparison subcircuit produces a plurality of comparison results in accordance with the relationship between the first value and the first predetermined threshold value and the second predetermined threshold value.

8. The system of claim 7 wherein the comparison subcircuit produces a first comparison result when the first value is less than the first predetermined threshold value, a second comparison result when the first value is intermediate the first predetermined threshold value and the second predetermined threshold value, and a third comparison result when the first predetermined value is greater than the second predetermined threshold value.

9. The system of claim 8 wherein the processing circuit further comprises an output subcircuit coupled to the comparison subcircuit and producing a first output signal responsive to the first comparison result, a second output signal responsive to the second comparison result and a third output signal responsive to the third comparison result.

10. The system of claim 2 further comprising a relay coupled to the comparison subcircuit.

11. The system of claim 10 wherein the processing circuit includes a timer coupled to the relay.

12. A water sensing system for sensing water in a liquid comprising:

a water sensor capable of being coupled to the liquid to produce a first signal having a first value indicative of a relative water content of the liquid;

a temperature sensor capable of being coupled to the liquid to produce a second signal having a second value indicative of a temperature of the liquid; and

a processing circuit coupled to the water sensor and the temperature sensor to produce in response to the first and second signals a third signal having a third value indicative of an absolute water content of the liquid.

13. The system of claim 12 wherein the processing circuit includes a display for displaying the first, second, and third values.

14. The system of claim 13 further comprising a switch to switch the display between the first, second, and third values.

15. The system of claim 12 wherein the processing circuit comprises a memory device which stores a look-up table relating the third value to the first and second values.

16. The system of claim 12 wherein the processing circuit comprises a memory device which stores an algorithm relating the third value to the first and second values.

17. A water sensing system for sensing water in a liquid comprising:

a water sensor capable of being coupled to the liquid to produce a first signal having a first value indicative of the water content of the liquid;

a processing circuit coupled to the water sensor including a noise isolation subcircuit which receives the first signal and produces a second signal electrically isolated from the first signal.

18. A liquid purification system for sensing and removing water from a liquid comprising:

a water sensor capable of being coupled to the liquid to produce a first signal having a first value indicative of a water content of the liquid;

a processing circuit coupled to the water sensor to produce at least one output signal; and

a purifier coupled to the sensor circuit to remove water from the liquid in response to the output signal.

19. The system of claim 18 wherein the purifier comprises at least one of a spinning disk purifier, a nozzle purifier, and a tower purifier.

20. The system of claim 18 further comprising a particle filter operatively associated with the purifier to remove particles from the liquid.

21. The system of claim 18 wherein the processing circuit comprises a comparison subcircuit including first and second threshold values, the second threshold value being greater than the first threshold value, the comparison subcircuit producing a first output signal when the first value is greater than the first threshold value, a second output signal when the first value is between the first and second threshold values, and producing a third output signal when the first value is greater than the second threshold value; and

the purifier is actuated responsive to the third output signal and deactuated responsive to the first output signal.

22. A water sensing system for sensing water in a liquid comprising:

a water sensor capable of being coupled to a liquid to detect the water content of the liquid; and

a processing circuit including a water sensor calibration subcircuit coupled to the water sensor to electronically calibrate the water sensor.

23. The system of claim 22 further comprising a temperature sensor capable of being coupled to the liquid to sense the temperature of the liquid and wherein the processing circuit further comprises a temperature calibration subcircuit coupled to the temperature sensor to electronically calibrate the temperature sensor.

24. The system of claim 22 wherein the water sensor and the processing circuit comprise a portable unit.

25. The system of claim 24 wherein the portable unit is battery-powered.

26. A water sensing system for sensing water in a liquid comprising:

a water sensor capable of being coupled to a liquid to sense the water content of the liquid;

a temperature sensor capable of being coupled to the liquid to sense the temperature of the liquid; and

a processing circuit including a temperature calibration subcircuit coupled to the temperature sensor to calibrate the temperature sensor.

27. The system of claim 26 wherein the processing circuit further comprises a water sensor calibration subcircuit coupled to the water sensor to electronically calibrate the water sensor.

28. A method for sensing water in a liquid comprising:

sensing a relative water content value of the liquid;

sensing a temperature of the liquid; and

electronically converting the relative water content value to an absolute water content value.

29. The method of claim 28 wherein electronically converting the relative water content value to an absolute water content value comprises using a look-up table.

30. The method of claim 29 wherein electronically converting the relative water content value to an absolute water content value comprises using an algorithm.

31. A method for removing water from a liquid comprising:

sensing a water content of the liquid;

producing a signal indicative of the water content; and

actuating a purifier to remove water from the liquid in response to the signal indicative of the water content.

32. A method for calibrating a water sensor comprising:

measuring the water content of a first medium having a first known water content value using a water sensor probe to produce a first output signal;

measuring the water content of a second medium having a second known water content value using the water sensor probe to produce a second output signal; and

electronically calibrating the water sensor using the first and second known values and the first and second output signals.

33. The method of claim 32 further comprising:

adjusting a first displayed water content value to be equal to the first known water content value; and

adjusting a second displayed water content value to be equal to the second known water content value, wherein electronically calibrating the water sensor includes using the first and second displayed values.

34. A method for calibrating a temperature sensor used in a water sensing system comprising:

measuring the temperature of a temperature sensor probe using an external device; and

electronically calibrating the temperature sensor using the temperature measured by the external device.

35. The method of claim 34 wherein electronically calibrating the temperature sensor includes adjusting a displayed temperature value to be equal to the value measured by the external device.

36. A water sensing system for sensing water in liquids comprising:

a water sensor capable of being coupled to a liquid to produce a signal indicative of the water content of a liquid;

a display coupled to the water sensor for visually indicating the water content in response to the signal; and

a light intensity control circuit coupled to the display for maintaining a substantially constant perceived luminous intensity of the display when power supplied to the display fluctuates.

37. A method for programming a water sensor to convert from relative to absolute water content comprising:

obtaining a sample of a liquid;

determining a first relative water content of the sample using a water sensor probe;

adding a predetermined quantity of water to the sample;

determining a second water content value of the sample using the water sensor probe;

calculating a saturation level for the liquid based on the first and second relative water content values and the quantity of water added; and

storing the saturation level as a conversion factor to convert from relative to absolute water constant values for the liquid.

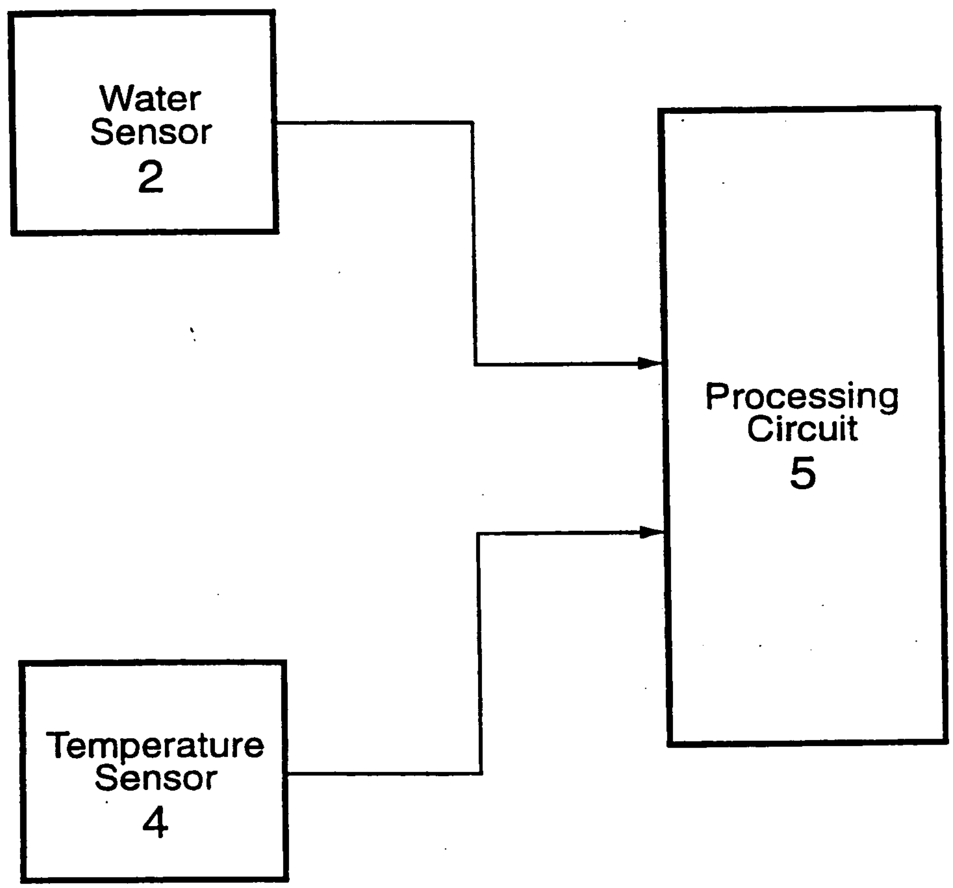


FIG. 1

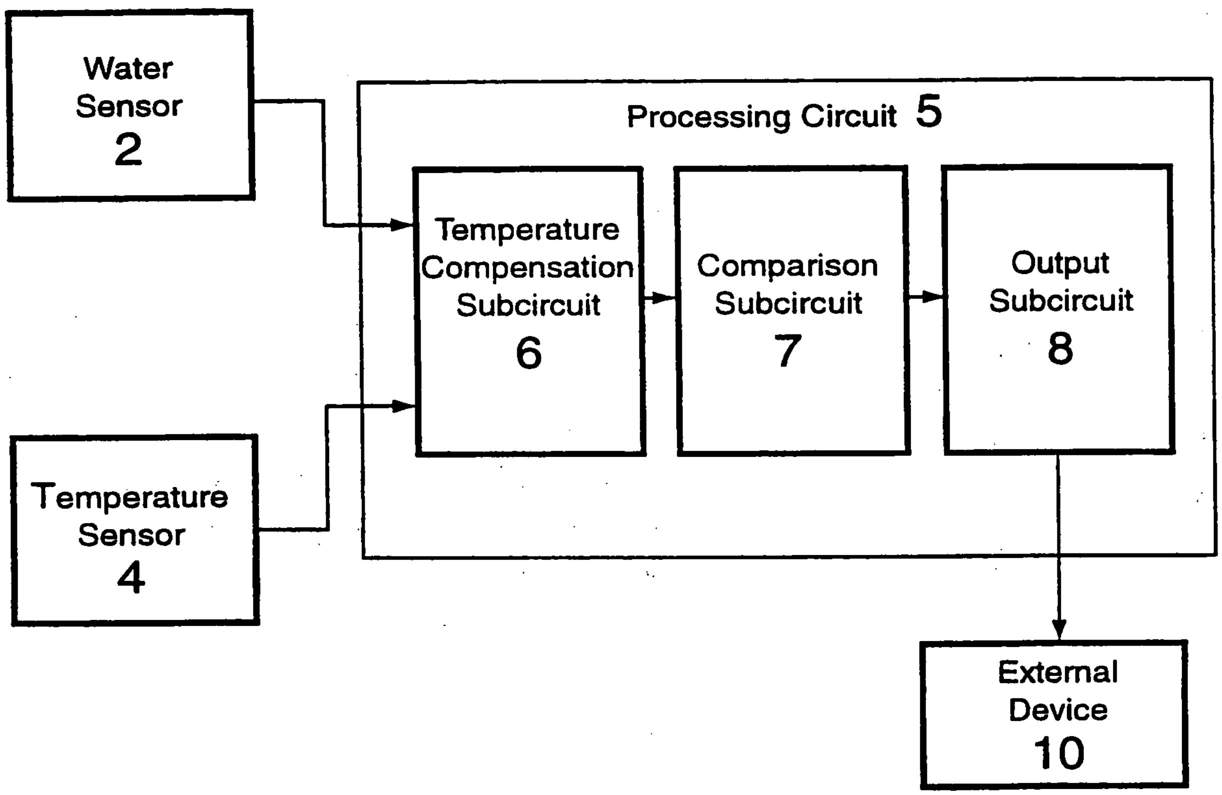

Water Sensor 2
Processing Circuit 5
Temperature Compensation Subcircuit 6
Comparison Subcircuit 7
Output Subcircuit 8
Temperature Sensor 4
External Device 10

FIG. 2

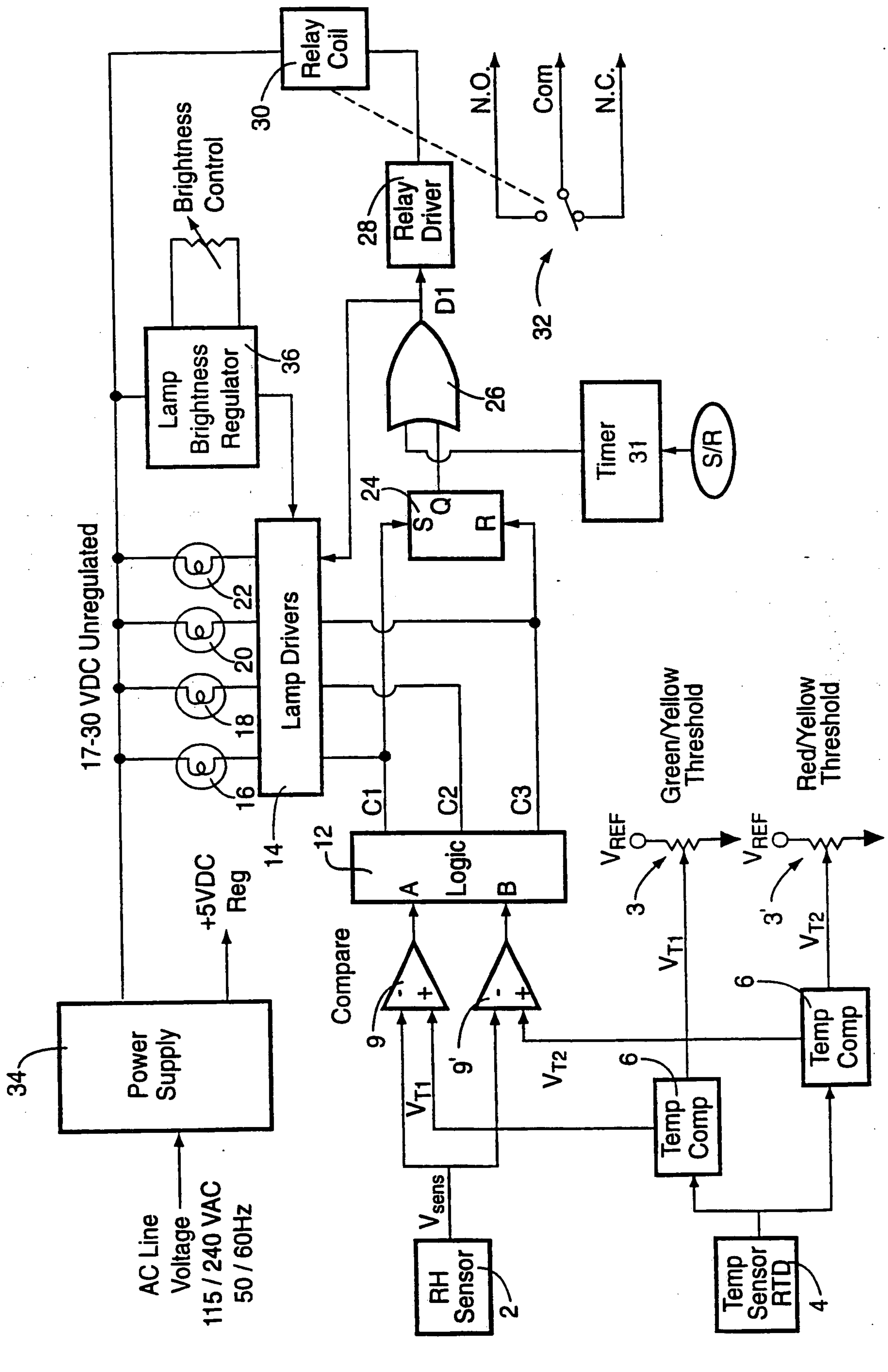

Relay Coil
30
Brightness Control
N.O.
Com
N.C.
Relay Driver
28
32
D1
Lamp Brightness Regulator
36
26
Timer 31
S/R
17-30 VDC Unregulated
24
S
Q
R
Lamp Drivers
22
20
18
16
14
C1
C2
C3
12
Logic
A
B
+5VDC Reg
Green/Yellow Threshold
Red/Yellow Threshold
V_{REF}
V_{REF}
3
3'
Compare
V_{T1}
V_{T2}
6
6
Temp Comp
Temp Comp
9
9'
Power Supply
34
V_{T1}
V_{T2}
V_{sens}
AC Line Voltage 115 / 240 VAC 50 / 60Hz
RH Sensor
2
Temp Sensor RTD
4

FIG. 3

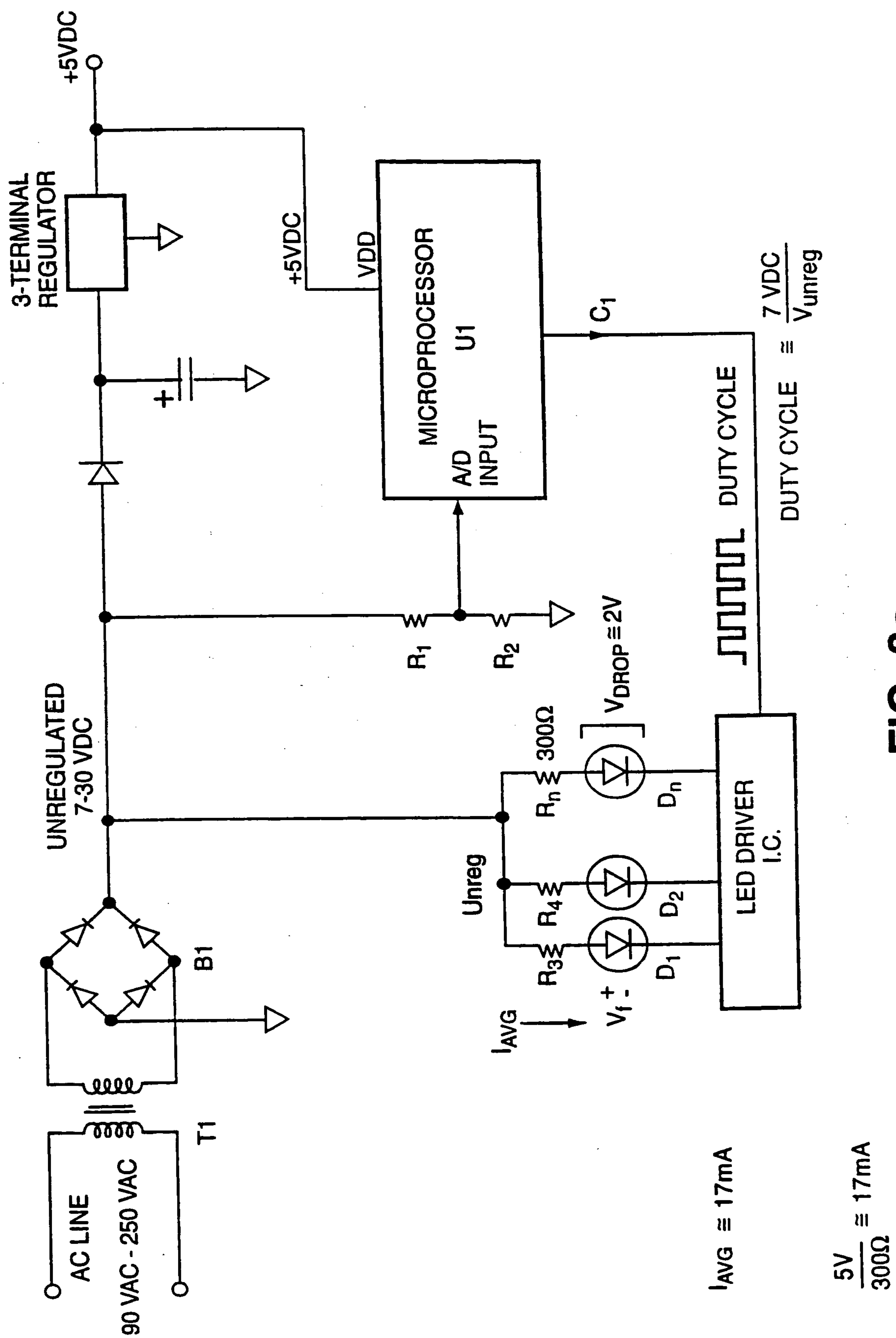

+5VDC
3-TERMINAL REGULATOR
+5VDC
VDD
MICROPROCESSOR
U1
A/D INPUT
C_1
DUTY CYCLE
DUTY CYCLE $\cong \frac{7\text{ VDC}}{V_{unreg}}$
UNREGULATED 7-30 VDC
R_1
R_2
$V_{DROP} \cong 2V$
300Ω
R_n
D_n
Unreg
R_4
D_2
R_3
D_1
LED DRIVER I.C.
B1
I_{AVG}
V_f + -
T1
AC LINE
90 VAC - 250 VAC
$I_{AVG} \cong 17mA$
$\frac{5V}{300\Omega} \cong 17mA$

FIG. 3a

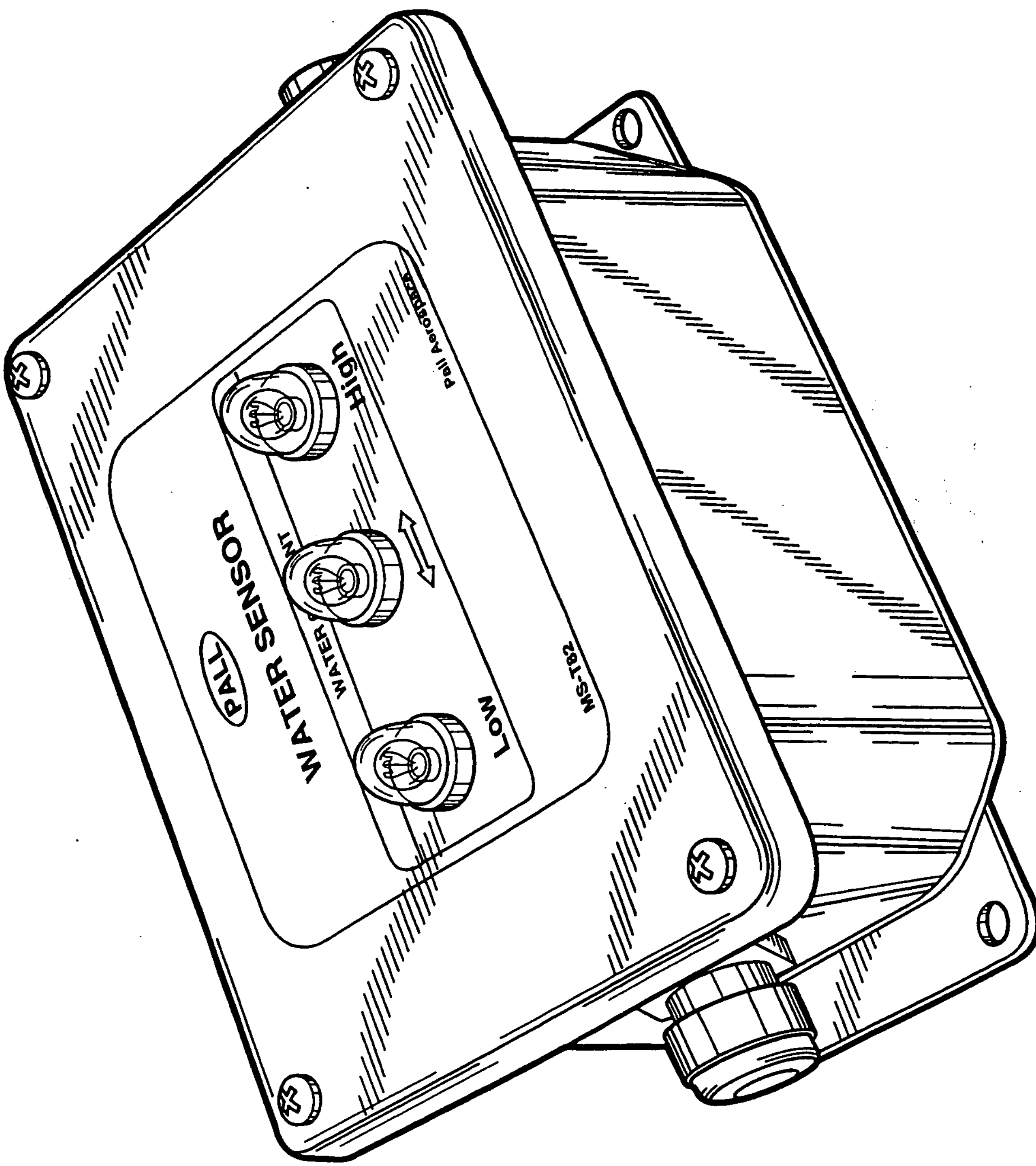


FIG. 3b

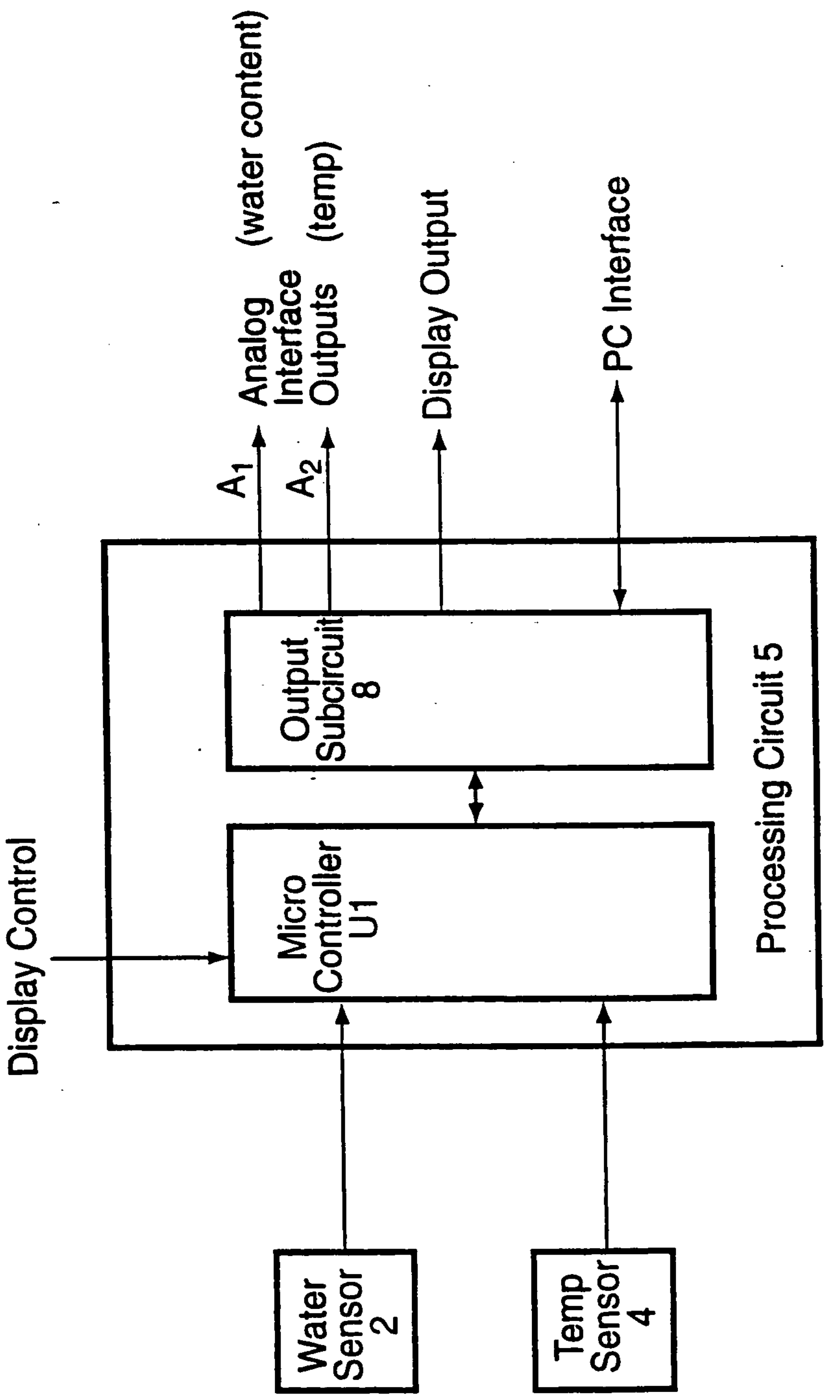
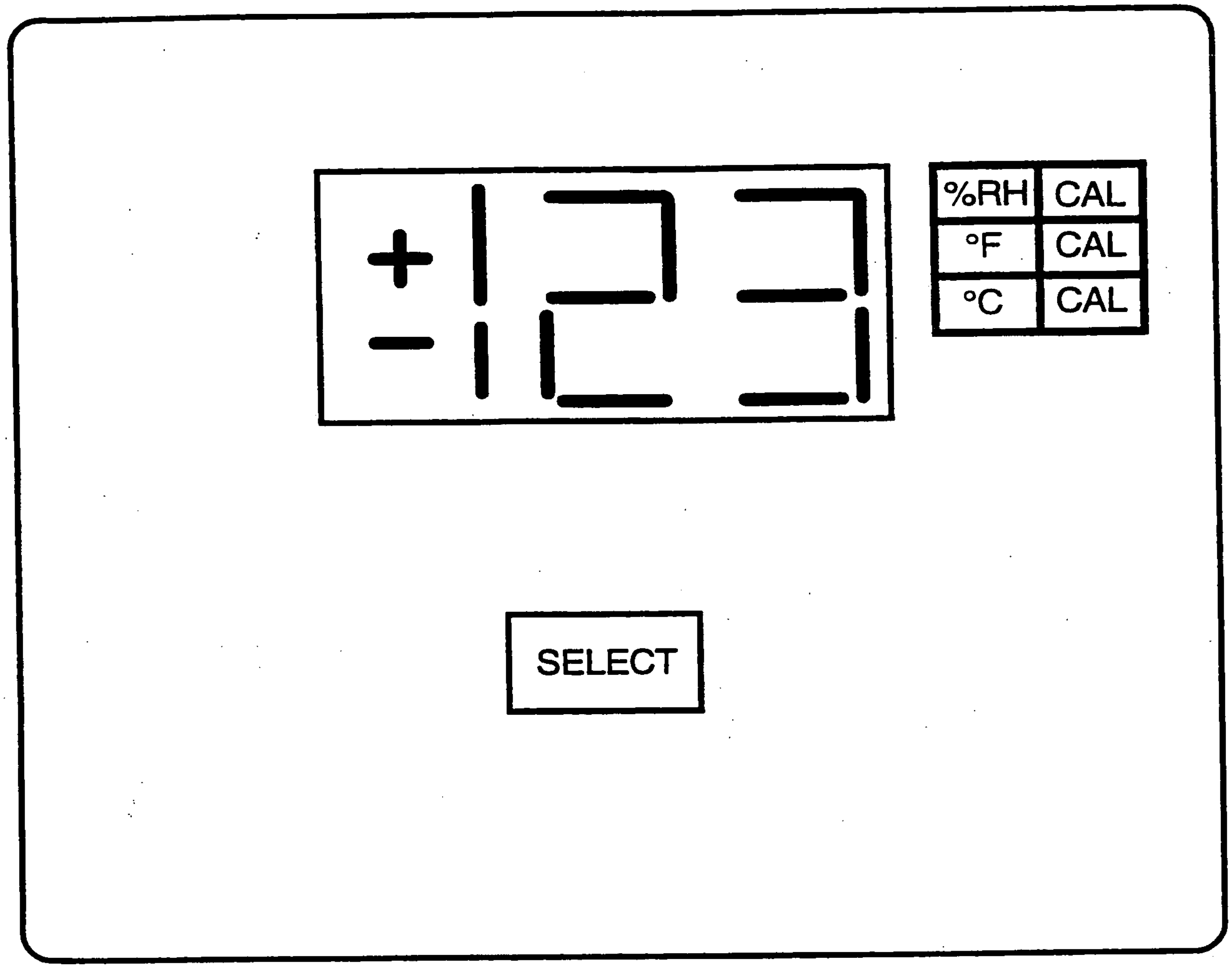

Analog Interface Outputs
(water content)
(temp)
A_1
A_2
Display Output
PC Interface
Display Control
Output Subcircuit 8
Micro Controller U1
Processing Circuit 5
Water Sensor 2
Temp Sensor 4

FIG. 4



INTERNAL SWITCHES:

1. RH CAL
2. TEMP CAL
3. °F / °C UNITS SELECT
4. MOVE HIGHER (PUSH BUTTON)
5. MOVE LOWER (PUSH BUTTON)

FIG. 5

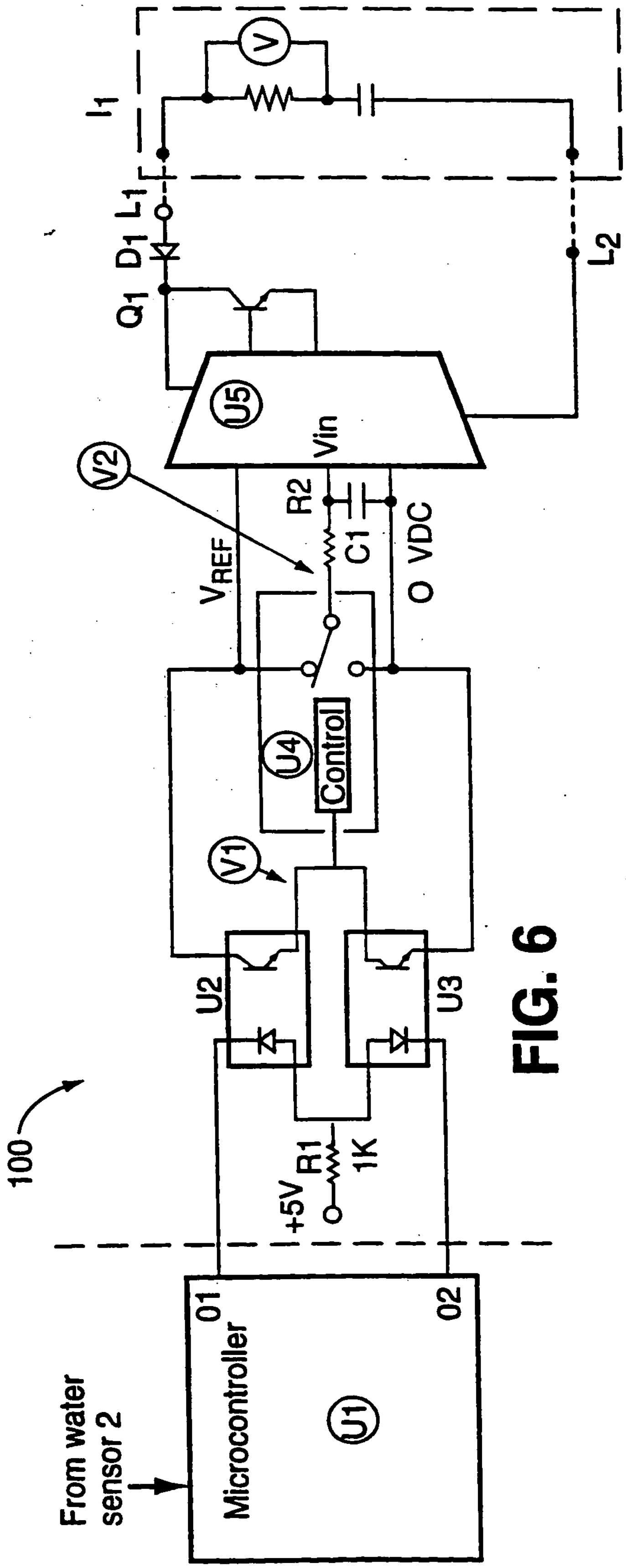


FIG. 6

Water Sensor
Isolated Interface
4-20 mA Analog Output

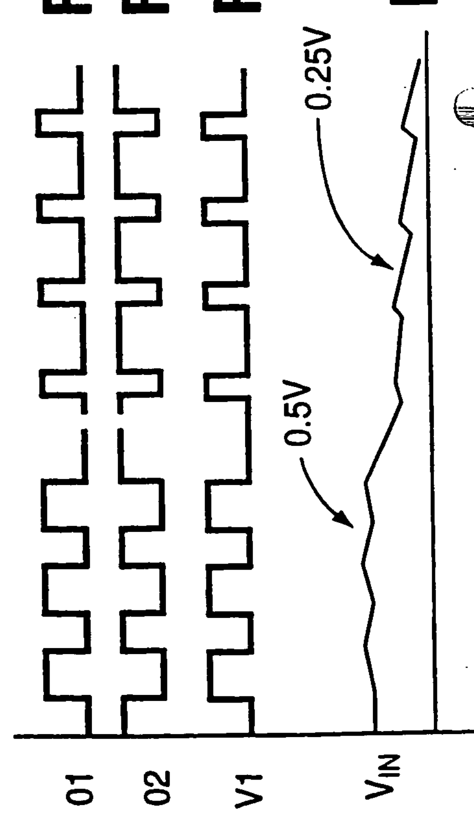


FIG. 7a
FIG. 7b
FIG. 7c
FIG. 7d

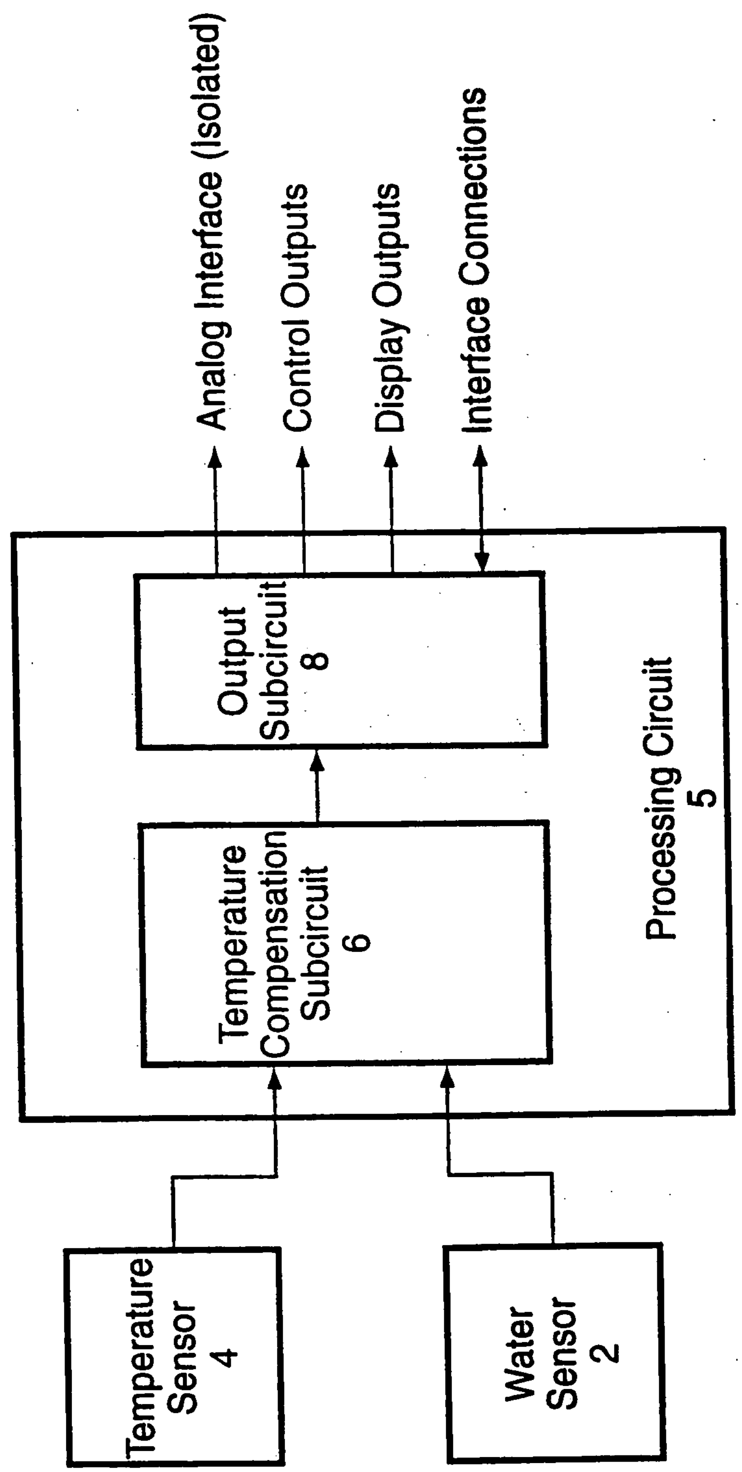
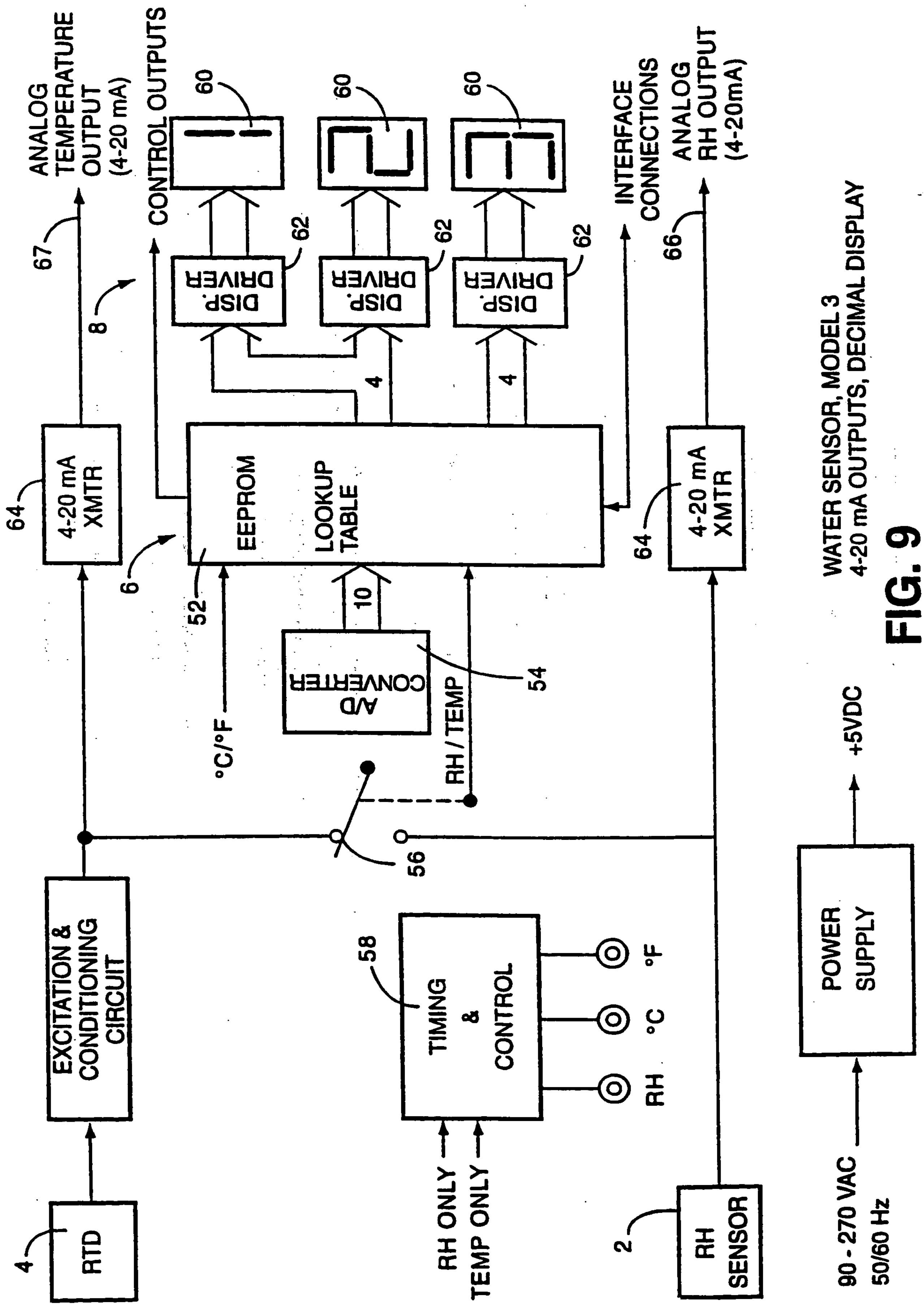

Analog Interface (Isolated)
Control Outputs
Display Outputs
Interface Connections
Output Subcircuit 8
Temperature Compensation Subcircuit 6
Processing Circuit 5
Temperature Sensor 4
Water Sensor 2

FIG. 8



WATER SENSOR, MODEL 3
4-20 mA OUTPUTS, DECIMAL DISPLAY

FIG. 9

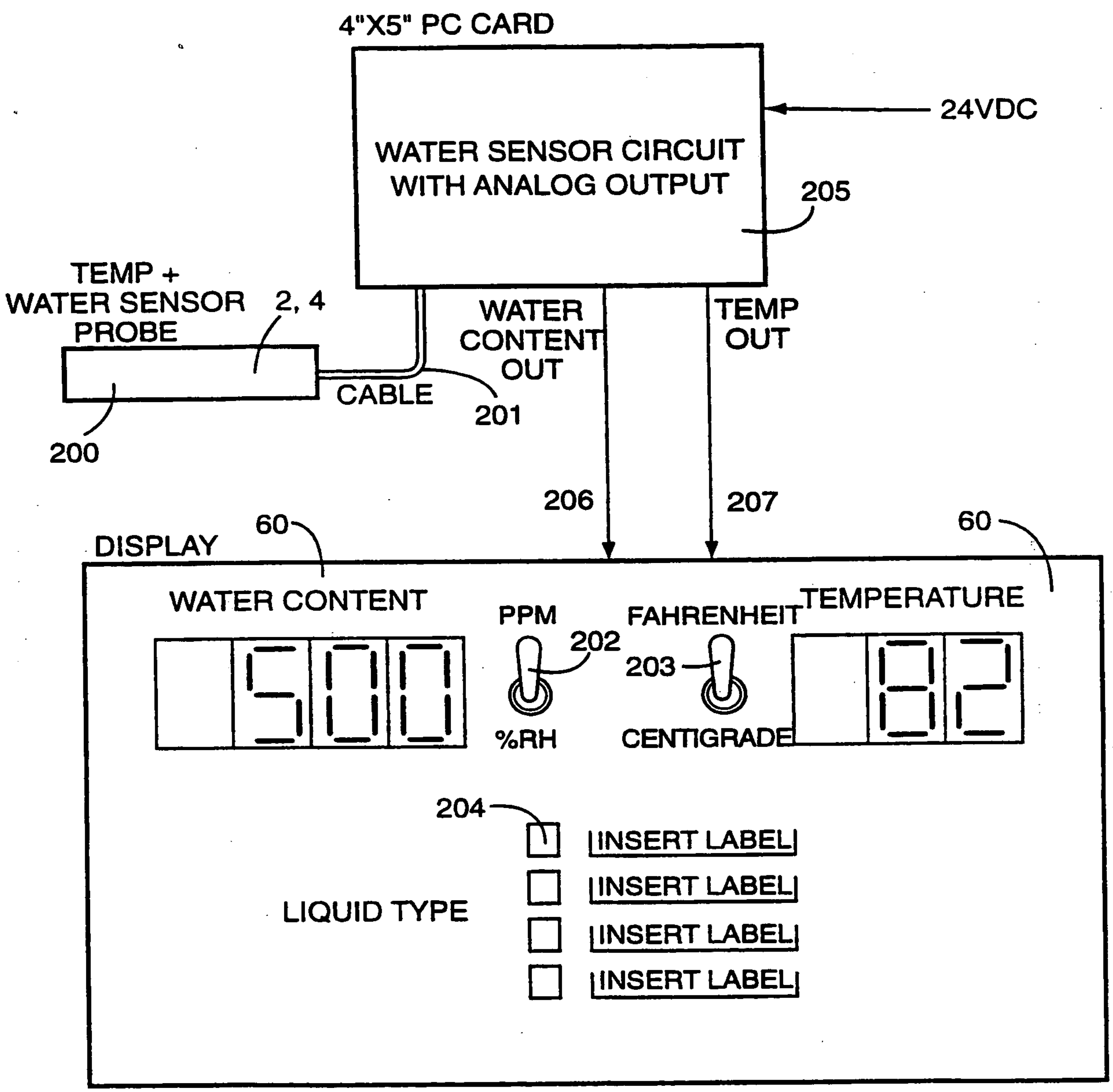

4"X5" PC CARD
WATER SENSOR CIRCUIT
WITH ANALOG OUTPUT
24VDC
205
TEMP +
WATER SENSOR
PROBE
2, 4
WATER
CONTENT
OUT
TEMP
OUT
CABLE
201
200
206
207
DISPLAY
60
60
WATER CONTENT
PPM
202
%RH
FAHRENHEIT
203
CENTIGRADE
TEMPERATURE
204
LIQUID TYPE
INSERT LABEL
INSERT LABEL
INSERT LABEL
INSERT LABEL

FIG. 10

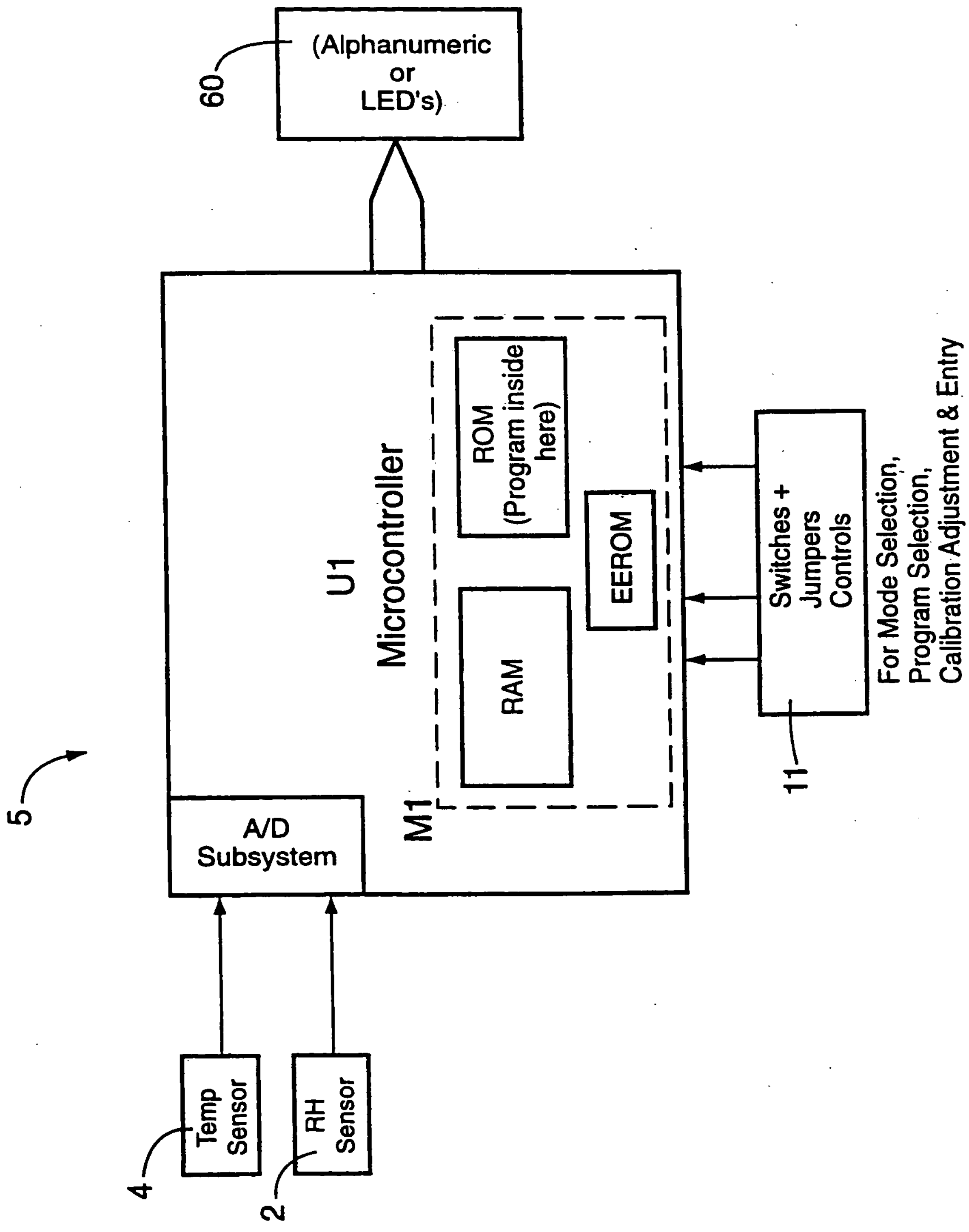

(Alphanumeric
or
LED's)
60
U1
Microcontroller
ROM
(Program inside
here)
EEROM
RAM
M1
A/D
Subsystem
5
Switches +
Jumpers
Controls
For Mode Selection,
Program Selection,
Calibration Adjustment & Entry
11
Temp
Sensor
4
RH
Sensor
2

FIG. 11

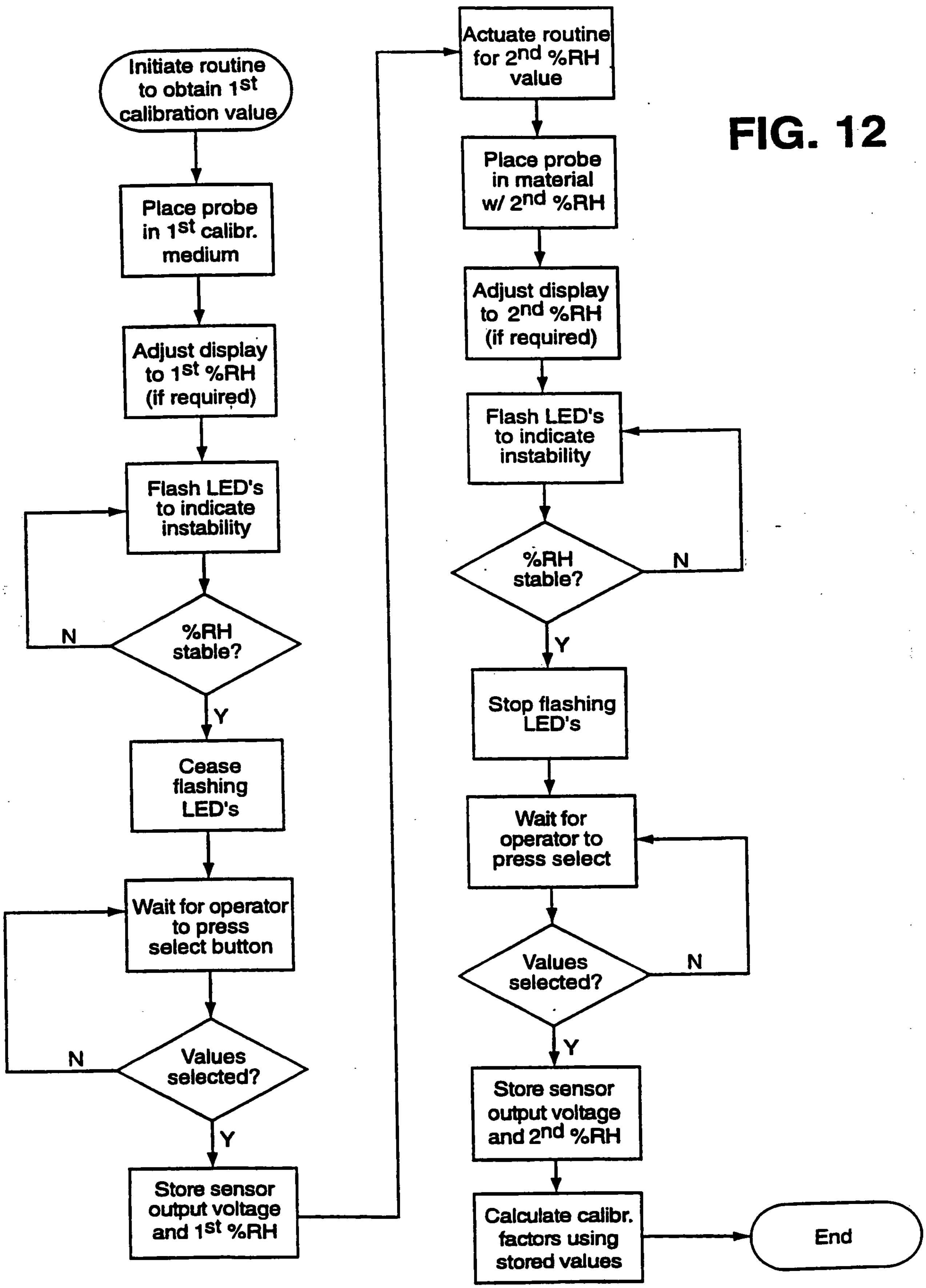

Initiate routine to obtain 1st calibration value
Place probe in 1st calibr. medium
Adjust display to 1st %RH (if required)
Flash LED's to indicate instability
%RH stable?
N
Y
Cease flashing LED's
Wait for operator to press select button
Values selected?
N
Y
Store sensor output voltage and 1st %RH
Actuate routine for 2nd %RH value
Place probe in material w/ 2nd %RH
Adjust display to 2nd %RH (if required)
Flash LED's to indicate instability
%RH stable?
N
Y
Stop flashing LED's
Wait for operator to press select
Values selected?
N
Y
Store sensor output voltage and 2nd %RH
Calculate calibr. factors using stored values
End

FIG. 12

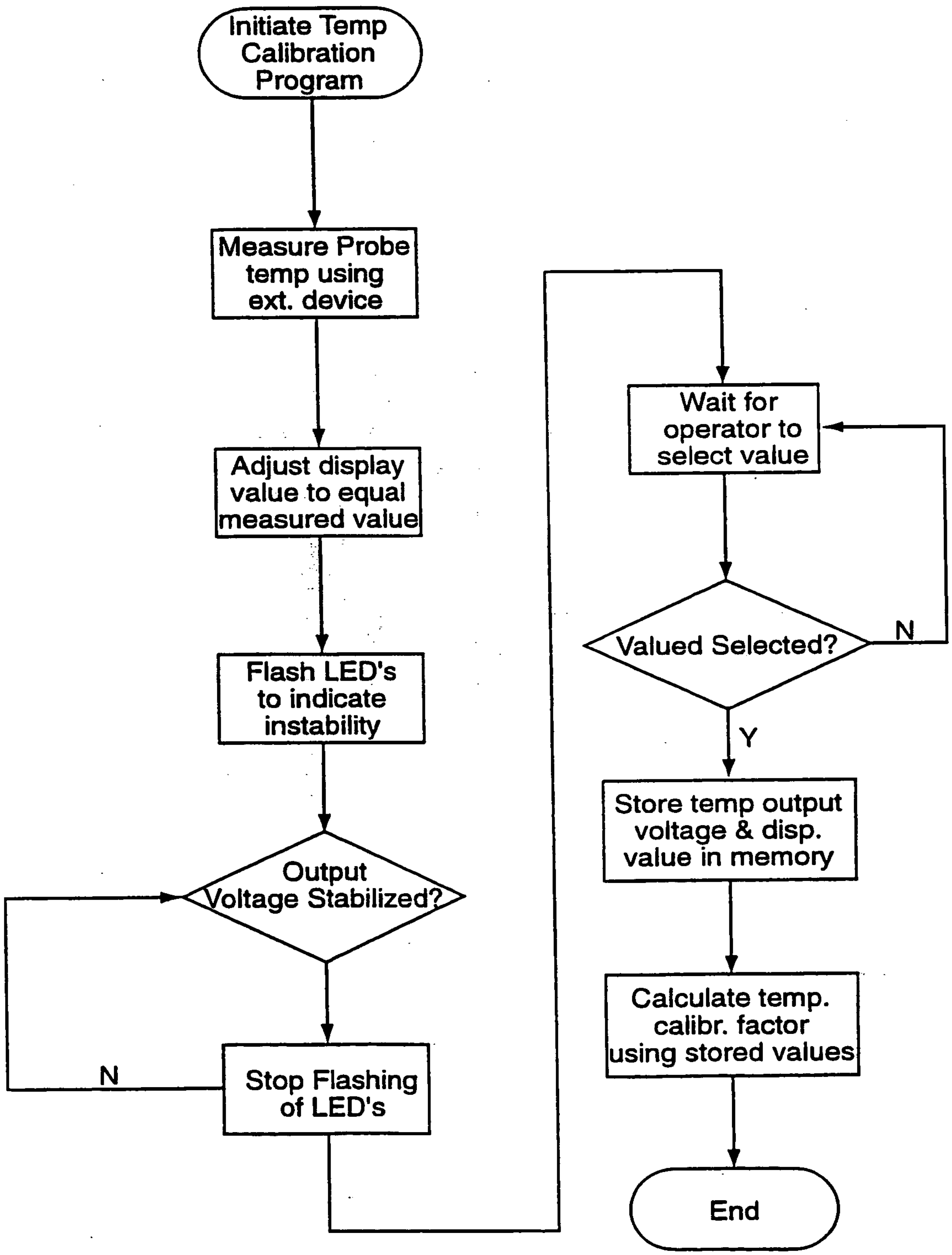

Initiate Temp Calibration Program
Measure Probe temp using equal ext. device
Adjust display value to equal measured value
Flash LED's to indicate instability
Output Voltage Stabilized?
N
Stop Flashing of LED's
Wait for operator to select value
Valued Selected?
N
Y
Store temp output voltage & disp. value in memory
Calculate temp. calibr. factor using stored values
End

FIG. 13

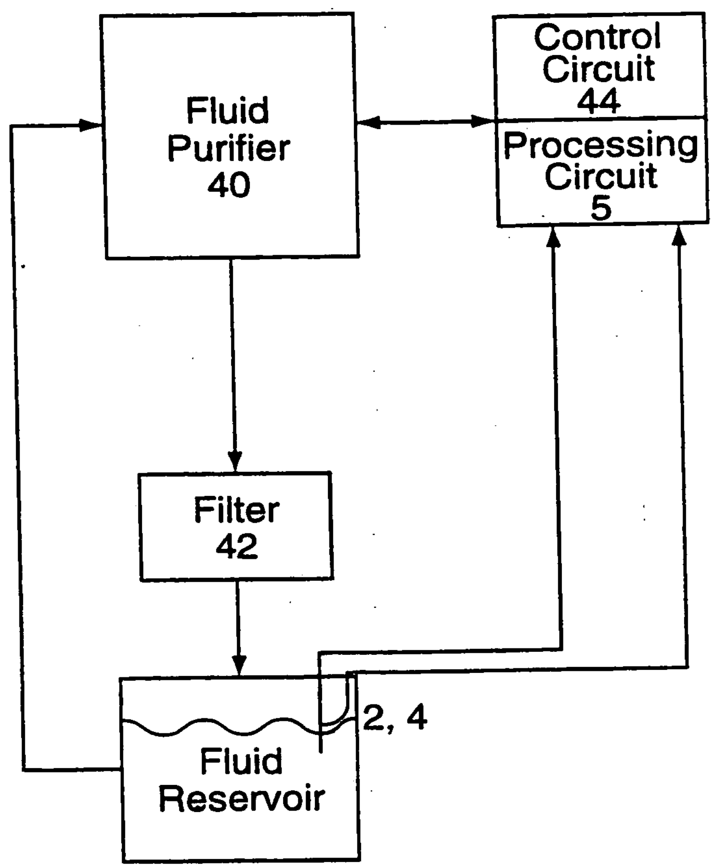

Fluid
Purifier
40
Control
Circuit
44
Processing
Circuit
5
Filter
42
2, 4
Fluid
Reservoir

FIG. 14

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